THE RACING & HIGH-PERFORMANCE TIRE

Using the Tires to Tune for Grip and Balance

by

Paul Haney

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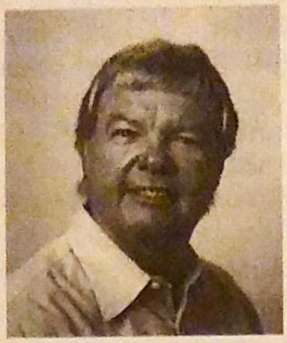

Paul Haney

"Motor racing offers the boldest technical and athletic challenges of our time. It is a thoroughly modern human invention, a combination of athletics, science, and business, driven by enthusiastic fans, adolescent male energy, and corporate funding. Racers have an amazing faith that a budget, people, a driver, cars, engines, and a schedule of race events justify a lifestyle that demands endless air travel, and total, lifetime personal commitment 24/7. Racers believe that on-track test sessions inevitably result in meaningful information, suggesting hardware and software changes that lead to performance gains, and that through track-test data analysis, a tire model, sims, driver feedback, a wind tunnel program, 'chemistry,' the 'right package,' and more time on the 7-post rig we might explain those changes, and discover new changes to test again, thereby plunging repeatedly into new terrain hoping the world will somehow become clearer, lap times quicker, and we will finally grasp the strange truth of the tires. And the universe will prove to be cheerfully connected, and races will be won, if the pit-stop strategy works."
—Paul Haney, Sept. 2002 with apologies to Edward O. Wilson.

INTRODUCTION

A SUCCESSFUL END TO A LONG QUEST

This book is the result of 15 years of work. After getting actively involved in racing in 1987, it took me 10 years to figure out that tires are by far the most important component on a racecar, or any road vehicle for that matter. After another five years researching tires with no help or encouragement from any racing-tire manufacturer except for Hoosier, I'm ready to publish this book.

This is the first book ever that explains, clearly I hope, some of the complexities of rubber, how a pneumatic tire generates grip, and describes how to tune for grip and balance using the load sensitivity of tires. Drivers of everyday road vehicles, as well as racers, will find this book informative.

Books on vehicle dynamics are available but they are mostly written by academics who emphasize mathematics rather than clear explanation of how things really work. Carroll Smith's books got me started and are priceless to the hands-on racer. *Race Car Vehicle Dynamics* by the Millikens, Bill and Doug, is the best academic work by far and should be in every racer's library. But all these books left me still asking, "Why?" So I labored to create my own explanations for how a four-tired vehicle generates grip. If any reader fails to understand any topic in this book, then I didn't explain it well enough.

Am I Just Stupid?

Why did it take so long for me to generate the explanations in this book? Am I just stupid? Maybe, but if so I'm in good company. I've been in contact with some of the smartest people in racing, and only a very few of them offered any assistance or had any coherent response to my questions.

Maybe racecar engineers just don't want to spread their knowledge around. They've worked hard learning what they know, and they're finally making a living at it, and they don't want to spread their secrets around. I used that excuse for them for a long time.

Racing is full of people who work hard and act like they know what they're doing, but don't really know WHY they do those things. I don't know how to credit this quote, but it sums up the situation: "It's almost as bad to qualify on the pole and not know why as it is to fail to qualify and not know why."

Ignorance, Confusion, and Paranoia

As I learned more about the technical aspects of racing, I began to ask more specific questions. If you ask the right question you get a useful answer, even if that answer is "I can't talk about that." When I hear that I know I'm on the right track.

Asking the same question of several different people also works. Often I could put together answers from several people and learn more than any of the individuals had told me. One tire manufacturer assigned one of their guys to me, and the other people answered questions by referring me to him.

The complexity of motor racing prevents the development of confidence among racing technical people. They have a working model in their heads, but they aren't willing or able to describe it. I think some of these people are so unsure about what they think they know, that they become convinced an attempt at an explanation would reveal their ignorance.

Tires are by far the most important component on a racecar, but good information is almost nonexistent. Nature abhors a vacuum, so people make up stories about how tires work. That's useful as long as the stories get updated with new information. Clinging to old, disproved theories is not useful.

Some racers can't tell what's important and what isn't. They won't talk about anything technical, because if their ideas are right they're giving away valuable secrets, and if they're wrong they've revealed their ignorance. Some people won't even talk shop with their own teammates. They're so paranoid, they hide everything. When I meet guys like that I'm polite, I just don't try to talk about anything technical.

I get the idea that some of these people would engage in a conversation, but find it difficult to describe that model in their heads. When somebody like me comes around asking questions, their response is likely to sound like doubletalk, because we're just not talking the same language. This is frustrating to all of us.

I don't expect everyone earning a living in racing to tell me all they know, but I think many people could learn a lot by asking each other questions and sharing information more freely. Unfortunately most racers fear that the last good idea they had is the last good idea they'll ever have!

Some Help from a Few People

My conversations with technical people at races vary considerably. Most people are friendly. Some say very little about anything technical, and no one has ever offered a comprehensive explanation of their work. Early on I met Jeff Braun, a race engineer who like myself has a mechanical engineering degree, and he helped with the first book. We coauthored *Inside Racing Technology* which sold well and is now out of print. Jeff knows that the model in his head changes constantly. He uses what he thinks he knows and changes his model when new information dictates.

Jim Hamilton, software simulation wizard, is one of the few race engineers with both hands-on knowledge and top-notch analytical skills. Good friends Ted and Nancy James have been very helpful and supportive. Claude Rouelle, the only guy actually teaching all he knows about racing and making a living at it, helped me understand several important concepts. Alec Purdy, a highly underrated race engineer, helped me explain roll centers.

Bruce Foss of Hoosier Racing Tires and Frank Secondari of Kumho Tires have both been very helpful. Frank understands a lot about the almost infinite trade-offs inherent in tire development, and explained many of them to me. Engineers from the big-name race tire manufacturers have rarely been helpful, but Al Speyer of Bridgestone-Firestone, Inc. has been supportive and participated in an interview that appears in the book.

There is one person without whom this book would not have happened. Kevin Cameron writes about motorcycles for *Cycle World* magazine and, in my opinion, is the best Motorsports technical writer in the business. After a phone conversation about tires, Kevin sent me four books that provided me with some basic information on tires and got me started on the project. Thanks, Kevin!

A notably open group in racing are the technical product suppliers, makers of shock absorbers and friction products, for example. The shock guys know they're dealing with a product that is extremely complicated in its use, and they're pretty open about what they know, because they're certain they'll learn more every day. These people support their customers by sharing their own development information without spreading any one team's hard-won knowledge among the other teams. They do a great job and are fun to be around in spite of, or maybe because of, their brutal travel schedule.

Tire Companies Confused Also

The pneumatic tire as a consumer product is an amazingly reliable, irreplaceable device and a real bargain. And tires continue to improve, giving more wet and dry grip and wearing better to boot. But the tire manufacturers have committed the unforgivable sin of blaming their customers for their own failures, mainly abominable product marketing. "People don't like to buy tires," whined one tire person.

The pneumatic tire might be the most useful and complicated device humans make, but the tire manufacturers provide no useful information to their customers. People are forced to buy tires mainly on the basis of price and company reputation. Even race teams get tire data only sporadically, and that data is pretty useless anyway. Tire performance is necessarily highly dynamic, but tire data comes mainly from testing under static conditions.

For the first 10 years I was involved with racing, I just assumed that tires were a fully-characterized, fully-engineered product. I assumed tire engineers knew how tires worked and how to manufacture them consistently. When I began to ask questions of tire engineers, they double-talked me and avoided giving me any useful information, and I believed them when they said they were protecting proprietary information.

But as I learned more about tires, and asked more detailed questions, I began to believe that the tire engineers weren't so much avoiding answering my questions as they were unable to do so. After I got upset at a guy for not giving me an answer to what I thought was a basic question, he looked around, came closer and whispered, "We don't know."

I Don't Know Everything Either

And don't think just because I wrote this book that I know everything about tires, vehicle dynamics, or anything else. In this book I'm sharing what I know at this time. A racecar is an extremely complicated device, and as I learn more I find more layers of questions. Hopefully I'll continue to learn. One of the reasons for publishing this book now is to put the information out there so that anyone who would like to point out errors or offer better information or clearer explanations can do just that. And then maybe I'll write another book!

My email is paul@tvmotorsports.com. Discussions of these topics will appear on insideracingtechnology.com.

"It's some simple things that make these cars go fast."

—Ed Nathman, CART engineer.

CHAPTER 1

HOW A CAR TURNS A CORNER

The pneumatic tire is arguably the most complicated and useful device man makes. Without tires we'd all be traveling in streetcars or on railroads, and none of us could live more than walking distance from a rail line. Cars, trucks, bicycles, motorcycles—none would be possible. That would be a different world!

Without rubber tires there is no way for a vehicle to make a turn at any speed above a crawl. Those horse-drawn carts of a hundred years ago turned corners because the horse pulled them around the corner. The rigid wood or metal tires on the early horseless carriages generated only enough lateral force to turn the vehicle at very low speeds. And the ride was bone-jarring.

A modern pneumatic tire is a complicated composite construction of strong, light polymer fibers held together in a matrix of viscoelastomeric polymers—rubbers. Specialized adhesives bond multiple components into a light, doughnut-shaped structure called a carcass. A flat band of rubber heat- and pressure-bonded onto the outside diameter of the carcass forms the traction surface, or tread. Reinforcing the carcass of a radial tire are belts of polymer thread or steel wire. A relatively thin sidewall connects the tread to the steel cables in the bead area that clamp the tire onto the wheel.

The pneumatic tire is a durable, inexpensive device that allows us to operate fast, convenient, safe personal vehicles, creating complete travel independence and a vast, flexible network of overland freight delivery.

Vehicle, Tires, Driver

Whether you're a race engineer or a club racer or an autocross competitor or an everyday high-speed driver of a car full of loved ones, you need to understand the relationship between the driver, the tires, and the vehicle. These three components determine safety and performance. This chapter presents how tires make it possible for a car to turn a corner safely and sets the stage for following chapters that present detail on the unique properties of rubber and the pneumatic tire.

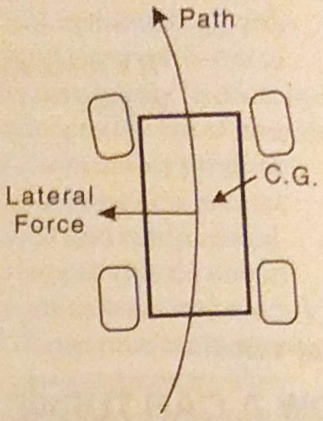

Fig. 1.1 Car on a Circular Path

Slip Angle

A vehicle turning a corner is on a path that is an arc of a circle. The radius of that arc might be changing, but at any instant the path is a specific arc. In order to maintain that path the car has to accelerate toward the center point of that arc. It takes a force to accelerate an object that has some mass (weight), and the tires are the source of that force. The cornering force that tires generate is called lateral force or side force or just grip. In Fig. 1.1 we combine the lateral forces of the four tires and have it acting on the center of gravity (CG) of the car.

We'll look at this in more technical detail in later chapters. For now I want to explain enough about how tires work so the reader can appreciate the information about rubber and tires in the next few chapters.

A tire produces lateral force with a slip angle, shown in Fig. 1.2. This slip angle, unique to the tire as a device, is the way a tire produces the lateral force necessary to turn a car. Slip angle happens when the steering wheel is turned from straight ahead, and it's the angle between where the tire is pointed and where the car is actually going. The term "slip angle" is slightly misleading because at

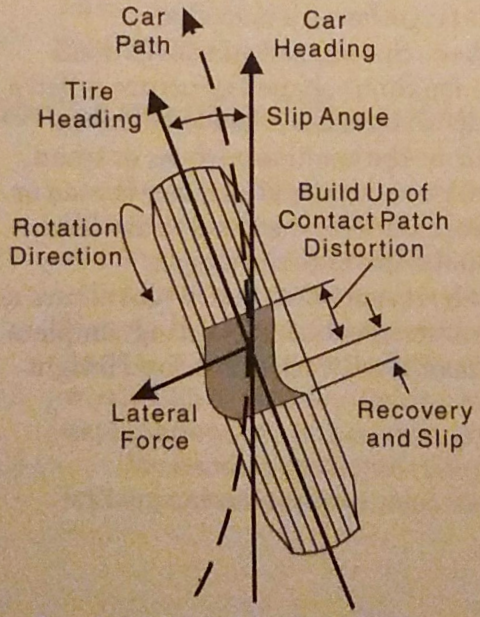

Fig. 1.2 Slip Angle, Bottom View

small slip angles there may be absolutely no slip or sliding in the contact patch. But we're stuck with this name for the phenomenon.

A tire is an elastic structure made of "rubber and string," as some of the tire guys say, but that simplification is deceiving. An elastic material such as rubber yields to an external force, resists movement with an opposing force, and recovers when the external force is removed. Steel is another highly elastic material. This elastic characteristic of a tire allows the tire to be pointed in a direction different from the direction the car is headed. This means the leading edge of the tread contacts the ground slightly to one side of the rest of the contact patch. As the tire rolls, each small increment of tread rubber coming onto the road sits down another small distance toward the direction the tire is pointed.

As the car's weight comes onto these small increments, they stick to the road. The tread is now pulling the rest of the tire and generating forces that go through the wheel and the suspension to turn the car. The force needed to change the car's path is generated by the tire and is called lateral force or side force.

Footsteps

We can use the analogy of a person walking to further explain slip angle. A person walking on a circular path changes direction in small increments. At each step a foot is turned in a small angle along the path of the arc. The heel contacts the ground and the rest of the shoe comes down in this new direction. As weight comes onto the shoe sole, the shoe is pointed in the new direction. The next step also changes the walker's path a small amount. These small changes continue to build up and the walker's path becomes an arc.

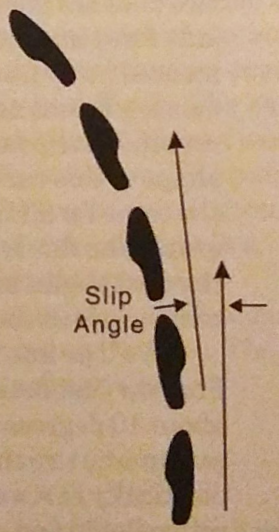

Fig. 1.3 Footstep Analogy for Slip Angle

That's exactly what happens when a tire is given some steering input. Each small increment of tread rubber rotating into contact with the road surface latches onto the road surface a small increment toward a new heading. As long as the steering input remains the same, each increment of the tread contacts the road a small amount toward the new direction. The rest of the contact patch thinks it's headed in the old direction but that portion is continually rotating out of road contact. The next time that part of the tire comes around and touches down, the heading of the tire and car will have changed.

The tire tread actually deforms as it rotates through the contact patch area and then recovers as the car's weight comes off the contact patch. The force needed to deform the tire is what produces the lateral force needed to change the path of the car.

What about the rear tires? When the front tires respond to steering input with a slip angle and begin to develop lateral forces, the front of the car turns to a new heading and the entire car rotates in that direction. If the rear wheels were mounted like casters they would swivel and the rear of the car would spin outward away from the turn. But the rear tires are fixed in direction and they resist with their own slip angles and lateral forces.

Lateral Force vs. Slip Angle

Fig. 1.4 shows the general relationship between the lateral force a tire generates and the slip angle of the tire. A tire does not generate side force until it is steered away from its current course and it assumes a slip angle. The shape of this curve is not the same for all tires. A graph like this is a specific characteristic of a tire design—the result of the cord angles and rubbers used in the tire structure and the rubber compounds in the tire tread.

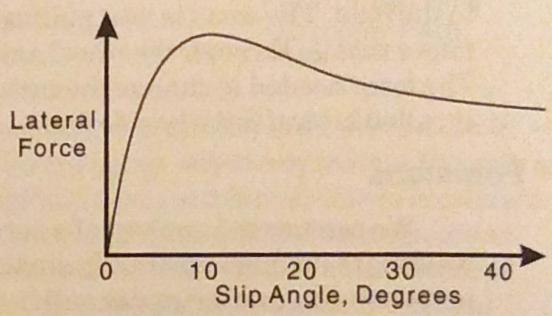

Fig. 1.4 Generic Curve, Lateral Force vs. Slip Angle

We'll go into more detail with this type of graph in a later chapter. For now just notice that lateral force falls off a bunch after it peaks at about 10 degrees slip angle. And be aware of the unique nature of the pneumatic tire that allows it to grip the road surface and also deform elastically in a way that allows us to maneuver a vehicle at high speeds controllably and safely.

An Automobile Is Easier to Make Than a Tire

We think of an automobile as a complicated device that's difficult to manufacture. Actually, every part of a car has a unique part number with drawings, specifications, and manufacturing instructions that ensure every unit with that part number is made exactly the same. Anyone with the necessary machinery and skills can make that part and it will be just like all the other parts with the same part number made by all the other

qualified suppliers. Similar manufacturing documentation and tooling ensures repeatable, reliable assembly of each unit. Every part can be inspected and tested for quality compliance.

Take a steel bolt for a simple example. Any bolt can be inspected and measured to determine its exact dimensions. Remove a small piece of metal from the bolt and you can determine what atomic elements are present in the steel and the amount of each element. Inspect 10 bolts and you can estimate the manufacturing tolerances. Test a couple of bolts to failure and you know the strength—in pure tensile stress or in fatigue stress (bending back and forth).

Not so with rubber tires. Rubber can't be shaped with precision in the way metals are machined. Also, a finished tire is bonded together into one unit and a complete inspection destroys many of the individual components. Truck and airplane tires are X-rayed to make sure parts aren't left out and there are no unbonded areas, but how well the whole thing is stuck together can't be quantified. The quality of every tire depends on the properties of the raw materials, the precision and repeatability of the manufacturing processes, and the motivation and skills of the humans operating the equipment.

Unlike a bolt, inspecting a small piece of a finished tire doesn't reveal much useful information. The processing time under heat and pressure changes materials in the tire such that identifying the exact ingredients at the beginning of the process may be difficult. The basic molecules making up some materials may change into different molecules or the same molecules connected in different ways. The individual elements—carbon, hydrogen, oxygen, nitrogen, silicon, iron—are still there. But many of the material components you find in a finished tire have changed during the manufacturing process.

The point here is that many different companies can and do make a car or a computer, but only a few companies can make tires. The tire is an extremely important, complicated, and useful device.

The Complexity Is Daunting

The technical literature related to rubber and tires are thick with statements describing the vast complexity of the pneumatic tire. Here are a few. I added bold type for emphasis.

"The complexity of the structure and behavior of the tire are such that no complete and satisfactory theory has been propounded."—Mr. Temple in *Mechanics of Pneumatic Tires*.

The following quote is from opening remarks by D. F. Moore before a technical session on the Fundamental Aspects of Rubber Friction at a symposium on The Physics of Tire Traction: Theory and Experiment, held at General Motors Research Laboratories, Warren, Mich., Oct., 8-9, 1973.

"Those of us who are active in research and development as applied to rubber-like materials are well aware of the **truly interdisciplinary nature of tire-to-ground traction.** Physics, chemistry, metallurgy, dynamics, tribology, thermodynamics, heat transfer, elasticity, viscoelasticity, rheology, elastohydrodynamics, and lubrication technology play complex and intertwined roles in determining the magnitude of the frictional coupling that ultimately exists in the contact patch. It has been claimed that at least **50 variables are operative during the simple free rolling of a pneumatic tire. Such complexity necessitates the adoption of a simplistic and intuitive approach** in seeking a further understanding of contact friction."

Another example:

"If you want to appreciate the complexity of a tire you need to know it has maybe 18 different components. Two of them, the bead and the belt, are made of steel. The others are some type **of polymeric system which can give a different mechanical response depending on time, temperature, or frequency variables in the operating conditions of the tire.** These components are all interlinked either in series or parallel or combinations thereof in both the normal—up and down—loading of the tire by the suspension, torsional for steering, and shear or lateral slip for acceleration and deceleration. Those 16 rubber components are comprised of maybe 12 to 15 ingredients on an average which have their own normal variation during production, especially natural rubber, which is a product of nature. **So if you look at all the permutations, you can figure out that a tire is relatively complicated.**"—Lou Gatti, manager of rubber technology, J.M. Huber Co.

And one last quote from *Mechanics of Pneumatic Tires*:

"**The combination of road, tire, vehicle, and driver forms one entity.** The mechanical characteristics of the tire in contact with the road must combine with the mechanics of the vehicle to help in producing operational characteristics of the tire-vehicle system which are satisfactory to the driver."

The statements above can be summarized by saying that the pneumatic tire is an irreplaceable component in any road-vehicle system and is so extremely complicated as to defy detail analysis. But, when smart people confront a complex device, they simplyfy and test and develop solutions that allow incremental advances in knowledge. Progress continues.

"All new theories begin as heresies and superstitions."
—Special Agent Fox Mulder, The X-Files, Fox TV Network, 1996.

CHAPTER 2

RUBBER

In its simplest form a pneumatic tire is a doughnut-shaped balloon with enough air pressure in it so four tires can support the weight of a car. The strength needed to hold internal pressure and external loads comes from a flexible but amazingly strong "construction" of textile "cords" bonded in a rubber matrix. Strong bands of steel wire called beads hold the inside diameter of the tire onto the wheel rim. A rubber "tread" glued onto the outer diameter of the construction provides a road-contact surface that has good traction and wear characteristics. Rubber, with its elasticity and natural adhesion, is what makes a tire so useful.

Rubber History

Rubber history is full of exaggeration and misinformation. Many of today's tire manufacturers are named for pioneers in rubber technology and they each want to be thought of as the inventor of rubber. I assembled this section from several seemingly credible sources.

About 2,500 years ago people in Central and South America discovered they could use the sap of a local tree to waterproof footwear and clothing. You can imagine this was pretty useful in a rain forest. These early rubber harvesters cut a slit in the trunk of the tree and systematically collected the white sap which we now call latex. They even developed a kind of processing system, heating the latex to produce elastic balls they used in games.

The Spanish Conquistadors of the 17th century were introduced to rubber while they were infecting New World natives with smallpox. They saw rubber in use in the form of the bouncing balls used in games by the inhabitants of Haiti; in stinking, sooty torches in Mexico; and also as a rain-resistant coating on the capes worn by the Amazonian Indians. A Spanish historian by the name of de Herrera-Tordesillas described rubber in his 17th century book, *The General History of the Vast Continent and Islands of the Americas*.

During the 1730s the honorary professors of the Académie Française in Paris were amazed to find a sticky, stinking, brown lump that displayed an incredible elasticity among samples sent to them from French explorer Charles Marie de la Condamine. About 50 years later the first serious product made from the new "jungle material" came about by chance when the English engineer Edward Nairne discovered a mistake on a pencil drawing and wanted to erase it. He reached for some breadcrumbs as was customary at the time but accidentally picked up a piece of rubber that was also lying on the table. To his astonishment he found it erased the pencil marks much more effectively than the breadcrumbs. Inspired by this discovery, Nairne obtained more pieces of rubber and sold them as "rubbers" because they were used for "rubbing out." This proved to be the first practical use for the material and we still use rubber erasers today.

By the beginning of the 19th century people were discovering the benefits of rubber. Many inventors devoted themselves to the development of this material and were constantly discovering new products and areas of application. In 1821 Brazil, which still had a monopoly on rubber, sent a large shipment of rubber shoes to New York, but people found they cracked in the winter and became sticky and smelly in the heat of summer. In spite of these problems factories were springing up across North America and Europe manufacturing products using

rubber, including bathing caps, shoes, horse blankets, and aprons. The first rubber factory in the world opened in Paris in 1803; the first in England was established in 1820.

In 1823 a Scottish chemist, Charles Macintosh, tried to produce waterproof textiles. His experiments included attempts to dissolve pieces of rubber in chemicals. He had the most success with naphtha. He spread the rubber paste on layers of cloth, pressed them together, and made them into a raincoat. Although it was water-repellent, the coat smelled when warmed by the sun and became hard and rigid when it was cold. Nevertheless, the British took to this new fashion item, and raincoats have been known in Britain as "mackintoshes" ever since. His niece, Elizabeth Pugh Barker, married a Frenchman and was the great-great aunt of the Michelin brothers.

Obsession

In the summer of 1834 a bankrupt hardware merchant from Philadelphia, Charles Goodyear, visited the New York retail store of the Roxbury India Rubber Co., America's first rubber manufacturer. He showed the store manager a new valve he had devised for rubber life preservers. The manager shook his head sadly. The company didn't need valves. It would be lucky to stay in business at all.

The "rubber fever" of the early 1830s had ended as suddenly as it had begun. At first everyone had wanted things made of the new waterproof gum from Brazil, and factories sprang up to meet the demand. Then abruptly the public had become fed up with the messy stuff which froze bone-hard in winter and turned glue-like in summer. Not one of the young rubber companies survived as long as five years. Investors lost millions. Rubber, everyone agreed, was through in America.

Goodyear had his first good look at rubber in that store. He had played with bits of it as a child, but now, at 34, he experienced a sudden curiosity and wonder about this mysterious "gum elastic." "There is probably no other inert substance," he said later, "which so excites the mind."

Returning to Philadelphia, Goodyear was clapped into jail for debt. It was not the first time nor the last. He asked his wife to bring him a batch of raw rubber and her rolling pin. Here, in his cell, Goodyear made his first rubber experiments, kneading and working the gum hour after hour.

If rubber was naturally adhesive, he reasoned, why couldn't a dry powder be mixed in to absorb its stickiness—perhaps the talc-like magnesia powder sold in drug stores? Out of jail again, he tried, with promising results.

He talked a boyhood friend into backing a small business. Charles, his wife, and their small daughters made up several hundred pairs of magnesia-dried rubber overshoes in their kitchen. But before he could market them summer came, and he watched his footwear sag into a shapeless paste.

Neighbors complained about Goodyear's smelly gum, so he moved his experiments to New York. There a friend gave him a fourth-floor tenement bedroom for his "laboratory." A brother-in-law came to his squalid quarters, lectured him about his hungry children, and advised him that rubber was dead. "I am the man to bring it back," Goodyear told him defiantly.

He was adding two drying agents to his rubber now, magnesia and quicklime, then boiling the mixture and getting a better product all the time. Impressed, a New York trade show awarded him a medal.

Goodyear lavished all the arts of decoration on his dingy rubber samples, painting them, gilding them, and embossing them. Running short of material one morning, he decided to re-use an old decorated sample and applied nitric acid to remove some bronze paint. The piece turned black, and Goodyear threw it away.

A few days later he remembered that somehow the blackened scrap had felt different. He retrieved it from his trash can and found he was right. The nitric acid had done something to the rubber, making it almost as smooth and dry as cloth. This was better rubber than anyone had ever made before.

A New York businessman advanced several thousand dollars to begin production, but the financial panic of 1837 promptly wiped out both the backer and the business. Destitute, Goodyear and his family camped in the abandoned rubber factory on Staten Island, living on fish he caught in the harbor.

In time Goodyear got new backing in Boston and again achieved momentary prosperity. His partners wangled a government contract for 150 mailbags to be manufactured by the nitric-acid process. After making the bags Goodyear was so sure of himself that he stored them in a warm room and took the family away for a month's vacation. When he returned the mailbags were melted. Underneath their "dry-as-cloth" surface lay the same old sticky gum.

After five futile years Goodyear was near rock bottom. Farmers around Woburn, Mass., where he now lived, gave his children milk and let them dig half-grown potatoes for food.

Serendipity

When trying to solve a complicated problem, it sometimes helps to be lucky. This certainly describes what led to the most important achievement in the manufacture of rubber. By the winter of 1839 Goodyear had added sulfur to the array of materials used in his experi-

ments. There are several tales about the discovery, but the most persistent story is that one February day he wandered into the Woburn, Mass. general store to show off his latest gum-and-sulfur formula. In response to laughter among those present, the usually mild-mannered little inventor got excited and waved his sticky fistful of gum in the air. It flew from his fingers and landed on the sizzling-hot potbellied stove.

When he tried to scrape the mess off the stove, he found that instead of melting like molasses, it had charred like leather. And around the charred area was a dry, springy brown rim. It was still "gum elastic," but so remarkably altered that it was virtually a new substance. Charles Goodyear had finally made weatherproof rubber.

This discovery is often cited as one of history's most celebrated "accidents," but Goodyear stoutly denied it. Like Newton's falling apple, he maintained the hot-stove incident held meaning only for the man "whose mind was prepared to draw an inference." That meant, he added simply, the one who had "applied himself most perseveringly to the subject."

The winter after Goodyear's discovery was the blackest of his life. Depressed and gout-racked, his health broken, he hobbled about his experiments on crutches. He knew now that heat and sulfur miraculously changed rubber. But how much heat, for how long? With endless patience he roasted bits of rubber in hot sand, steamed them over the tea kettle, and pressed them between hot irons. When his long-suffering wife took her bread from the oven he thrust in chunks of evil-smelling gum.

The Beginnings of a Recipe

The patent issued to Charles Goodyear in 1844 described mixing natural gum rubber with sulfur and white lead (lead carbonate) and forming a fabric by coating cotton batting with the product and heating it to 270 degrees Fahrenheit. A typical composition was 20 parts of sulfur and 28 parts of white lead to 100 parts of India rubber. He dissolved the rubber in turpentine and ground the white lead and sulfur separately in turpentine as in making paint. These three ingredients were then spread on a smooth surface to form a sheet, and then exposed to heat. The patent also included a process that used heated cylinders or calender-rollers to mix the three ingredients. Amazingly a calendering process is still used in cord-reinforced rubber manufacturing today.

Goodyear wrote to the wealthy New York brother-in-law, the one who had once lectured him about his parental shortcomings, telling him of the discovery. The brother-in-law, a textile manufacturer, was interested when Charles told him that interwoven rubber threads would produce the fashionable puckered effect then much favored in

men's shirts. Two "shirred goods" factories were rushed into production and, on the ruffled shirtfronts of dandies, rubber rode to world-wide success.

As soon as he could, Goodyear disposed of the manufacturing interests which might have made him a millionaire and went back to his experiments. He wanted to use rubber to make everything: bank notes, musical instruments, flags, jewelry, ship sails, even ships themselves. He had his portrait painted on rubber, his calling cards engraved on it, his autobiography printed on and bound in it. He wore rubber hats, vests, and ties.

Goodyear, a true visionary, saw natural latex rubber as what we know it is today: the first and most versatile of modern polymers.

Parallel Development

Goodyear was slow in filing foreign patent applications. But he had sent samples of his heat-and-sulfur-treated gum to British rubber companies without revealing details. An English inventor named Brockedon showed Thomas Hancock, who had been trying for 20 years to make weatherproof rubber, some samples of the material Goodyear had patented. Hancock noticed a yellowish sulfur "bloom" on the surface of a Goodyear sample. With that clue, he developed a process for curing rubber in 1843, four years after Goodyear.

Thomas Hancock was to the British rubber industry what Charles Goodyear was to the American counterpart. His experiments showed rubber changed when immersed in liquid sulfur. The resulting material didn't stiffen when put on ice.

Like Goodyear, Hancock discovered vulcanization, a name coined by Brockedon from Vulcan, the ancient Roman god of fire. Hancock patented the process in 1843. By the time Goodyear applied for an English patent he found that Hancock had filed a few weeks earlier. Offered a half-share of the Hancock patent to drop a lawsuit, Goodyear foolishly declined and lost the suit.

When Goodyear died in 1860 he was $200,000 in debt. Eventually, however, accumulated royalties made his family financially comfortable. His son, Charles Jr., inherited something more precious than money—inventive talent—and later built a small fortune on shoemaking machinery. Neither Goodyear nor his family was ever connected with the company named in his honor, today's billion-dollar Goodyear Tire & Rubber Co.

Synthetic Rubber

Eventually people smuggled rubber-tree seeds out of Brazil and established natural rubber production in other areas of the world. But at the turn of the 20th century the ever-increasing uses found for

rubber and the increasing popularity of the horseless carriage created a demand for latex that rubber plantations couldn't satisfy. Natural rubber remained an expensive material motivating people to search for ways to produce an artificial substitute.

In 1909 Dr. Fritz Hoffman, a German chemist, filed a patent for the manufacture of synthetic rubber. He had polymerized isoprene, the basic molecular unit of the natural rubber polymer. Development continued and in 1929 rubber was made from butadiene-styrene copolymers.

World War II isolated the U.S. from Southeast Asian sources of natural rubber, resulting in a crash program to increase domestic production of synthetic rubber. The U.S. government built facilities to produce synthetic rubber and existing companies operated those plants. Annual production increased from 8,000 tons in 1941 to 820,000 tons in 1945. After the war those plants were sold to the rubber industry. Today about 70% of all rubber used is synthetic. Millions of tons of rubber are synthesized each year to supply a $60 billion international industry.

Charles Goodyear and the other people who worked hard to transform a gooey, smelly material into a useful product sowed the seeds of a materials industry that, 160 years later, is still in its infancy. Natural rubber is a polymer and its usefulness encouraged people to figure out how to make that polymer for themselves and go on to make many other polymers for new applications. Let's find out more about polymers in general and rubber in particular.

Rubber Is a Polymer

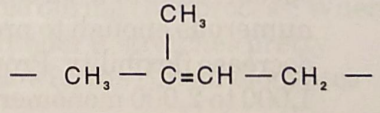

Fig. 2.1 Monomer Unit for Natural Rubber

Rubber is made up of long-chain, macromolecules called polymers. Think of a plate of spaghetti—long strings of pasta all mixed up and strung together. That's rubber at the molecular level. These long molecules are made up of repeating chemical units called monomers. Natural rubber, latex, is a mixture of polymers, but the most abundant constituent is isoprene, and latex is mainly a polyisoprene polymer.

Fig. 2.1 shows the isoprene monomer that, when repeated and bonded into a long chain, forms the polymer polyisoprene. Fig. 2.2 presents two polyisoprene chains crosslinked by sulfur bonds. The letters stand for atomic elements: C, carbon; H, hydrogen; S, sulfur.

Before being vulcanized, rubber is soft and easily deformed. Internally it can be thought of as a mass of slippery, tube-shaped molecules (as in the plate of spaghetti mentioned above) that slide among themselves when subjected to external forces. These long

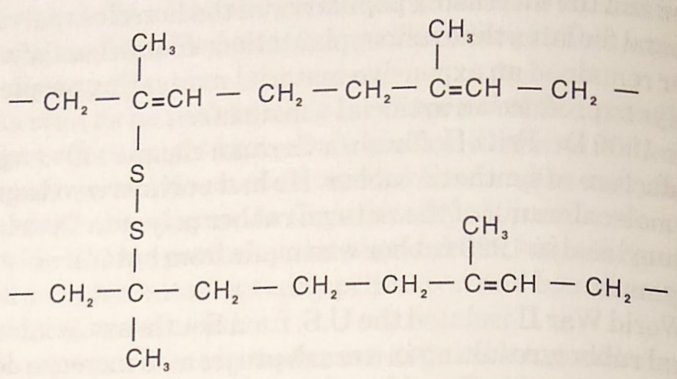

Fig. 2.2 Polymer Chains Crosslinked with Sulphur

molecules are entangled with themselves and each other. Where one chain lies close to another, a chemical bond can occur. These are called crosslinks. More than one type of polymer can be present and other materials might be present also. Chain length, flexibility, and interactions between chains are all extremely variable.

Goodyear's relatively simple vulcanization process used sulfur and heat to create crosslinks. The crosslinks don't form spontaneously but require some form of external energy. Even ultraviolet radiation in sunlight and ozone in the air can cause crosslinks. Tires exposed to sunlight and ambient air for long periods of time show sidewall surface cracks because of a loss of flexibility due to crosslinking. Vulcanization processes use chemical accelerants in rubber compounds and a specific time at a specified heat and pressure. The crosslinks must be numerous enough to prohibit plastic flow but not too numerous to decrease flexibility. Proper vulcanization results in molecules with 1,000 to 2,000 monomer units per chain and 10 to 40 crosslinks each.

The drawing in Fig. 2.3 is a simple representation of a network of polymer chains resulting from mixing and vulcanization. This processing creates entanglements and crosslinks among and between the long chains, transforming the raw rubber from a gooey, sticky material to a product with heat resistance and improved tensile strength.

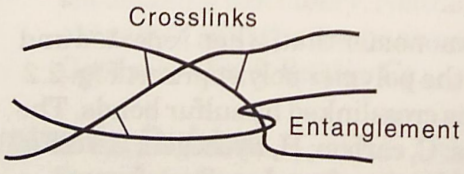

Fig. 2.3 Polymer Network after Vulcanization

Modern vulcanization processes use specific chemicals depending on the needs of the product in which the rubber will be used. We'll look at typical rubber recipes later.

Rubber Is Elastic and Viscoelastic

Steel is an elastic material. As long as it's not compressed or stretched past its elastic limit, a steel spring will recover to its original length after many deformation cycles. But even steel is not perfectly elastic, and repeated compression and extension will cause a temperature increase in a spring because a small part of the energy needed to deform the spring is retained in the material as heat rather than contributing to recovery.

Rubber is a generic term for a broad range of polymers that generate various levels of elastic response to an applied stress. A highly elastic rubber returns almost all of the energy input to it—a ball made of this material would bounce back almost to the level at which it was released. A ball made from a different rubber compound might hardly bounce at all. This energy loss in the material is called hysteresis. Since the energy loss mechanism in rubber is mainly due to viscous effects, these materials are said to be viscoelastic.

Creep Test

Here are a couple of examples of how a viscoelastic material like rubber responds to force inputs. It's these characteristics of rubber that make the pneumatic tire such a unique product.

Fig. 2.4 describes what happens when you deform a rubber sample by applying a force for some time and then remove the force. Let's say you hang a weight on a piece of rubber and after some time you take the weight off. The graph describes what happens if you measured the length of the rubber sample during that process. When you first put the weight on the piece of rubber it stretches pretty quickly to a longer length. Then, more slowly, the rubber elongates

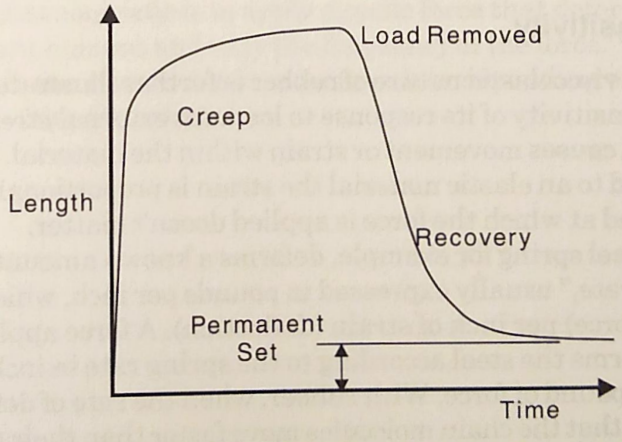

Fig. 2.4 Rubber Deformation with Load

farther. This is called creep. When the load is removed the rubber recovers toward its original length, but not all the way. The sample has taken a permanent set.

On the molecular level rubber is made up of long, flexible, chain-like molecules that form a loose, three-dimensional network in which the chains can change shape and slide past each other except at points where they are bonded to or entangled with their neighbor chains. An applied force causes the polymer chains to stretch, which means all those long chains have to coil or twist or move among themselves. Each element in the polymer network has to move in a viscous medium that includes all its neighbors so response to external force is slowed. If the external force is strong enough, some of the stretching involves the chains settling into new equilibrium positions or tearing or breaking bonds, which prevents complete recovery.

Mechanical Model for Rubber

Since rubber is a viscoelastic material it absorbs or dissipates energy when deflected by an external force. The amount of energy absorption depends on the damping factor of the rubber compound, defined as the energy dissipated divided by the energy applied.

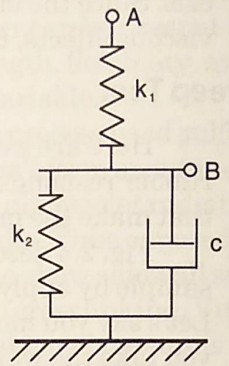

Fig. 2.5 Mechanical Model for Rubber

Fig. 2.5 is a schematic showing a mechanical model of rubber, a spring with a spring rate of k_1 in series with a parallel spring (k_2) and damper with a damping coefficient of c. If you apply a cyclic force at point A the rubber will deform mostly like a spring and give back the force applied to it, but also partly like a damper which is sensitive to the speed (frequency) of the applied force.

Speed Sensitivity

The viscoelastic nature of rubber is further illustrated by the speed sensitivity of its response to load. An external stress applied to a material causes movement or strain within the material. When a force is applied to an elastic material the strain is proportional to the stress. The speed at which the force is applied doesn't matter.

A steel spring for example, deforms a known amount. That's the "spring rate," usually expressed in pounds per inch, which is pounds of stress (force) per inch of strain (deflection). A force applied slowly still deforms the steel according to the spring rate in inches of deflection per pound of force. With rubber, when the rate of deformation requires that the chain molecules move faster than their normal

mobility allows, the resistance to deformation increases and the rubber is stiffer. When the deformation rate is low relative to the rubber's normal mobility, the viscous resistance to deformation is small. So a force moving faster meets more resistance than a force applied slowly. This is another viscoelastic characteristic of rubber.

Rubber Response to Cyclic Stress

Fig. 2.6 shows what happens if you apply a cyclic stress to a viscoelastic material. The solid line represents the input to the math model at point A. The dotted line describes the resulting motion at point B. The viscous reaction absorbs some of the input energy and the material's response to the stress is movement that is lower in value and lags in time. The energy loss, called hysteresis, shows up in an increase of temperature in the rubber.

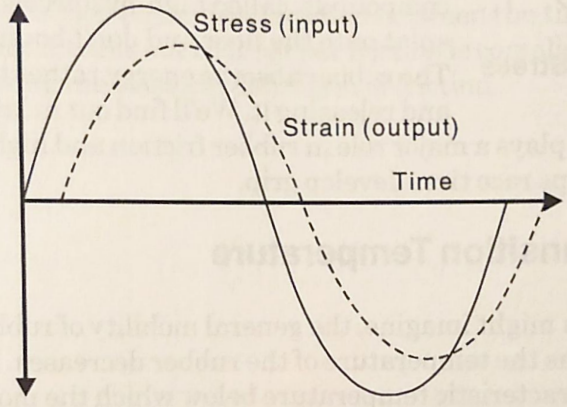

Fig. 2.6 Rubber Response to Cyclic Load

This means that a larger force will deform the rubber more quickly, just as a bigger bump moves a shock absorber faster. This is called speed sensitivity or frequency sensitivity. Another way to look at this characteristic is to apply a cyclic force that deforms the rubber a constant amount and vary the frequency of the force. You'll find that a viscoelastic system deforms more or less depending on the frequency of the disturbance.

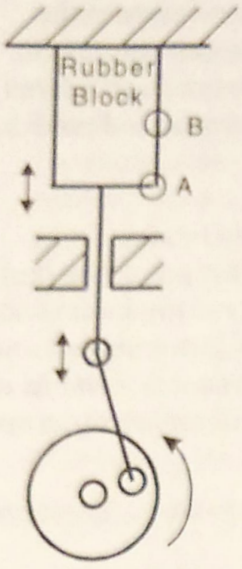

Fig. 2.7 Cyclic Stress

Fig. 2.7 is a schematic of a machine that would apply a cyclic force to a rubber block. The crank and rod rotate, generating a cyclically varying linear force at the surface of the rubber block, point A. The motion of the block at point A corresponds to the stress line in Fig. 2.6. Point B on the block would move similar to the dotted strain line in Fig. 2.6 due to energy absorption in the rubber block.

Actually rubber can be mixed—compounded—in various ways to produce materials with very different characteristics. You can buy solid rubber balls that are extremely elastic—when dropped from some distance they bounce back up almost to the release height. But other rubber compounds, called high-hysteresis rubber, just splat onto the floor and don't bounce back at all. The rubber absorbs energy rather than storing it and releasing it. We'll find out in later chapters that hysteresis plays a major role in rubber friction and high-hysteresis rubber helps race tires develop grip.

The Glass Transition Temperature

As you might imagine, the general mobility of rubber molecules decreases as the temperature of the rubber decreases. Most rubbers have a characteristic temperature below which the molecules lose their mobility. This is called the glass transition temperature, T_g, and varies from –250 degrees F for some silicone rubbers up to above 100 degrees F for polystyrene rubbers. Below T_g a rubber becomes rigid and immobile, a polymeric glass.

"Nothing happens in contradiction to Nature, only in contradiction to what we know of it."
—Special Agent Dana Scully, The X-Files, *FOX TV Network.*

CHAPTER 3

RUBBER FRICTION

In this chapter we're going to continue to discuss rubber. Obviously tire traction depends on friction between the tire and the road surface, but it turns out that rubber friction is complicated. Let's start by discussing the classical definition of friction.

Simple Friction

We need to overcome friction in order to move one material against another, a common phenomenon in our everyday world. Nails hold because of friction. We couldn't walk or even crawl without friction.

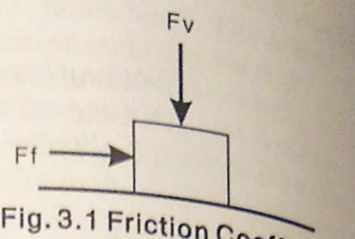

Fig. 3.1 Friction Coefficient
Ff = Cf x Fv

This general equation and Fig. 3.1 describe friction:

$F_f = C_f \times F_v$,

where Friction force (F_f) equals the coefficient of friction (C_f) times the vertical force (F_v).

This equation says the force necessary to move a material at a steady speed on another material is proportional to the force pressing the two materials together and also proportional to a nondimensional constant (C_f) produced by testing the two materials together. The static coefficient of friction is usually larger than the dynamic coefficient of friction for the same material. This means you need a little more force to start a material sliding than you do to keep the material moving at a steady speed.

Table 3-1: Typical Values of C_f for Combinations of Materials

Material	C_f
Wood on wood, dry	O.25 - 0.50
Metal on oak, dry	O.50
Leather on metal, dry	O.56
Metal on metal, dry	0.15 - 0.20
Rubber on glass, dry	2 +

A C_f greater than 1.0 means it takes more force to move a rubber block on glass than the force pressing the block onto the surface. This gives us a clue that with rubber there is more going on than simple friction.

Rubber Friction

Rubber generates friction in three major ways: adhesion, deformation, and wear. Fig. 3.2 describes these three components making up the total friction force experienced by a rubber slider moving across the surface of a road in the direction of speed V.

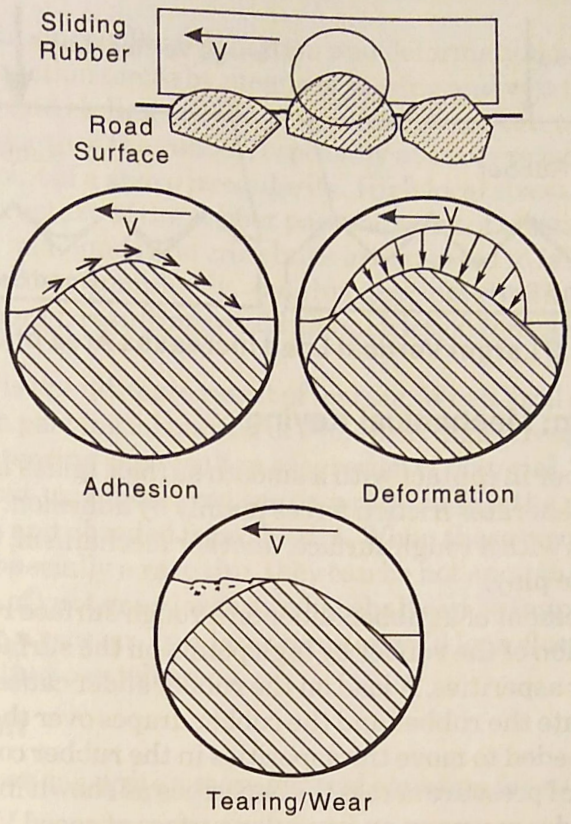

Fig. 3.2 Major Components of Rubber Friction

Adhesion

Adhesion is a property of rubber that causes it to stick to other materials, as we see with adhesive tape. Adhesion is generally thought to be the result of momentary molecular bonding between the two surfaces. If bond strength is the same at all the bond sites the force that resists sliding is proportional to the total of all the minute areas of contact. If the two surfaces were perfectly smooth the true area of contact would be the same as the observed area of contact, but this is not the case. Real surfaces are actually very rough on the molecular scale and contact is limited to the highest protuberances on each of the two surfaces. The true area of contact depends on the surface profiles, properties of the materials, and the contact pressure.

As you can see in Fig. 3.3, larger loads on the rubber presses the road irregularities into the rubber, increasing the contact area. More area in contact means more adhesion between the surfaces and higher friction forces. This situation satisfies the general requirements of the friction equation, $F_f = C_f \times F_v$.

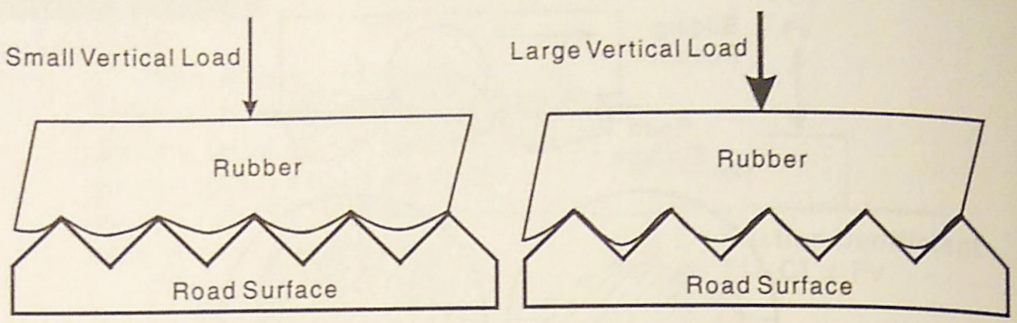

Fig. 3.3 Larger Vertical Load Increases Area of Contact

Deformation: Mechanical Keying

Rubber in contact with a smooth surface (glass is often used in testing) generates friction forces mainly by adhesion. When rubber is in contact with a rough surface, another mechanism, deformation, comes into play.

Movement of a rubber slider on a rough surface results in the deformation of the rubber by high points on the surface called irregularities or asperities. A load on the rubber slider causes the asperities to penetrate the rubber and the rubber drapes over the asperities. The energy needed to move the asperities in the rubber comes from the differential pressure across the asperities as shown in Fig. 3.4, where a rubber slider moves on an irregular surface at speed V.

A wet surface prevents contact between the rubber and the surface, blocking the formation of adhesive forces. Friction forces due to deformation, also called mechanical keying, provide most of the friction force between a tire and a wet surface.

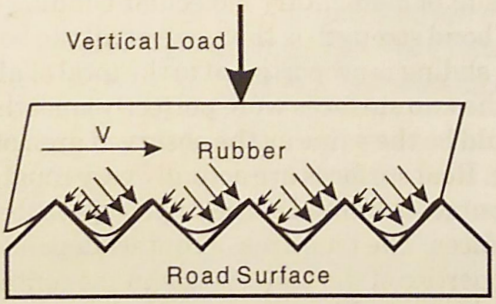

Fig. 3.4 Mechanical Keying, Differential Forces

Tearing and Wear

In addition to adhesive friction and deformation friction, rubber produces traction forces by means of tearing and wear. As deformation forces and sliding speeds go up, local stress can exceed the tensile strength of the rubber, especially at an increase in local stress near the point of a sharp irregularity. High local stress can deform the internal structure of the rubber past the point of elastic recovery. When polymer bonds and crosslinks are stressed to failure the material can't recover completely, and this can cause tearing. Tearing absorbs energy, resulting in additional friction forces in the contact surface.

Wear is the ultimate result of tearing. When local stresses increase in strength past initial tearing or remain at high strength for a period of time, that tearing can result in separation of material. The tire debris, bits of rolled-up rubber, you see on a racetrack is the result of rubber being torn and abraded from the tire. When these pieces separate from the tire, especially a race tire, they can be hot enough to stick together, so clumps of rubber as large as a baseball can be found on a racetrack or stuck to a racecar. In a later chapter we'll look closer at worn tires and what they can tell us.

Total Friction

Now we can write a more general equation for rubber friction:

$$F_{total} = F_{ad(hesive)} + F_{def(formation)} + F_{wear}$$

The naming of these components is strictly arbitrary. There are probably other friction components if you look in more detail, but we'll refer to them by these names in this discussion. Let's look in more detail at Fdef, deformation friction.

Deformation Friction and Viscoelasticity

Adhesive friction is the major contributor in tire traction, but it requires intimate contact between the two surfaces. Adhesive friction forces decrease drastically when the road surface is lubricated by dust, water, or ice. That's when deformation friction becomes more important.

Here's where another interesting property of rubber, viscoelasticity, comes into play. Rubber is elastic and conforms to surface irregularities. But rubber is also viscoelastic; it doesn't rebound fully after deformation. Press your thumbnail into a street tire and the rubber rebounds. Press it into a racing tire and the mark stays there, recover-

ing only slowly. This is a simple but crude test of hysteresis, or energy loss, in rubber. Low-hysteresis rubber rebounds quickly; high-hysteresis rubber lags in rebound after deformation.

Consider Fig. 3.5 where there is some sliding between the rubber and an irregular surface. If the rubber recovers slowly from the passing irregularity as in the high-hysteresis rubber, it can't push on the downstream surfaces of the irregularities as hard as it pushes on the upstream surfaces. This pressure difference between the upstream and downstream faces of the irregularity results in friction forces even when the surfaces are lubricated.

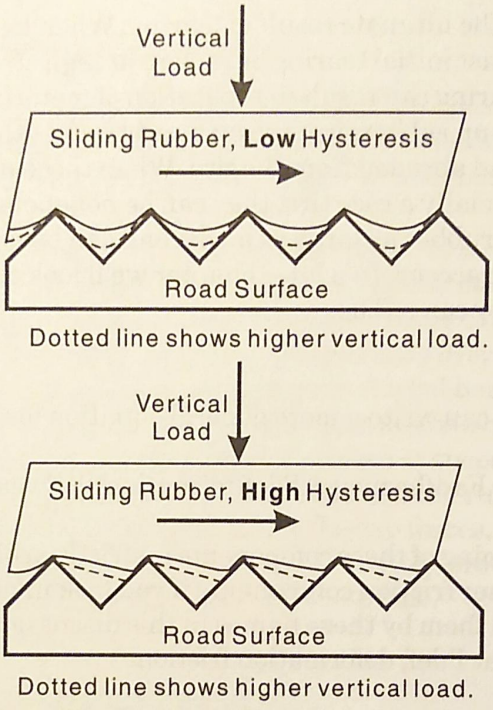

Fig. 3.5 Hysteresis in Sliding Rubber

An interesting analogy to rubber sliding past peaks in a road surface is a ship moving in water. We know a ship moving in water requires an engine and propeller to provide the necessary force to overcome fluid drag. The ship bumps into the still water at the bow and there is a little more pressure there than on the stern. It's this pressure difference acting over the wetted cross-sectional area of the ship's hull that is a part of the total drag the engines have to overcome. There is also viscous drag caused by the hull surface moving through the water.

Continuing with that same analogy, a ship traveling in "high-hysteresis water" would experience increased drag because the rubber would close in more slowly at the stern, creating a larger bow-to-stern pressure difference. In high-hysteresis rubber that's deformation friction. Fig. 3.5 depicts the concept of increasing pressure differences across asperities caused by high-hysteresis rubber.

A common test of hysteresis during rubber processing is called the rebound test. A rubber sample is formed into a flat, rectangular shape and attached to a wall. A steel ball on a string is anchored on the wall above the rubber sample. The ball is raised until the string is horizontal and taut. When released, the ball accelerates on the end of the string until it strikes the mounted sample. How far the ball rebounds is a measure of hysteresis. Short rebound is high hysteresis. If you're making a golf ball, you want the rubber to bounce the ball as far back as possible. If you're making tread rubber for race tires, you'd like the ball to splat against the wall with very little rebound.

Adhesive Friction and Surface Deformation

Fig. 3.6 shows the simple example of a smooth cylinder rolling on a soft rubber. The force needed to move the cylinder is the difference between forces of adhesion at the leading edge of the cylinder and the peeling of the rubber from the cylinder at the trailing edge. The energy needed to peel the rubber away from the cylinder is substantially more than the attractive energy during adhesion.

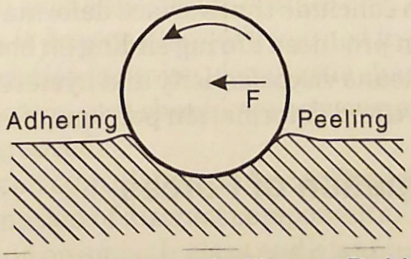

Fig. 3.6 Cylinder Rolling on Rubber

Fig. 3.7 shows a cross-sectional view of a glass hemisphere sliding on a soft rubber. The rubber adheres to the glass at the leading edge, but then waves of peeling and re-adhering move across the rubber surface in the direction of the sliding. These waves produce friction forces similar to the cylinder rolling on rubber. The energy required for the peeling is much higher than the energy gained in attachment.

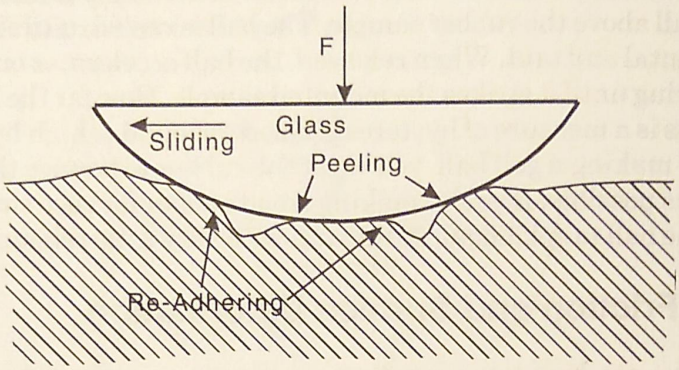

Fig. 3.7 Vicoelasticity in Adhesive Rubber Friction

We need to observe that these moving waves of attachment and peeling are similar to road asperities moving in a rubber slider. Both mechanisms deform the rubber. Because it has viscoelastic properties, the rubber absorbs some energy requiring more force to move the slider. So we can conclude that surface deformation is a key element in rubber friction produced during sliding on both smooth and rough surfaces. That means viscoelasticity and hysteresis figure strongly in both the adhesive and deformation portions of rubber friction.

Friction: A Combination of Forces

The graphs in Fig. 3.8 present data taken using a specific rubber polymer sliding on smooth glass and also a silicon-carbide sandpaper. The vertical scale is C_f, the coefficient of friction relating the friction force to the force pressing the rubber against a surface. The horizontal scale is the logarithm of the sliding speed.

Data taken from a rubber slider on glass produces a curve with a peak just above a Cf of 2.2. The curve falls off on each side of the peak because the rubber produces lower friction forces at slower and faster speeds. The same rubber on clean sandpaper peaks at a higher C_f and a higher speed. The distance "a" between the two curves is the difference in C_f at that sliding speed between this rubber on a smooth

surface and this rubber on a rough surface. Since Fad dominates on a smooth surface, it appears that a portion of that Fad is lost on a rough surface, probably because of reduced contact area.

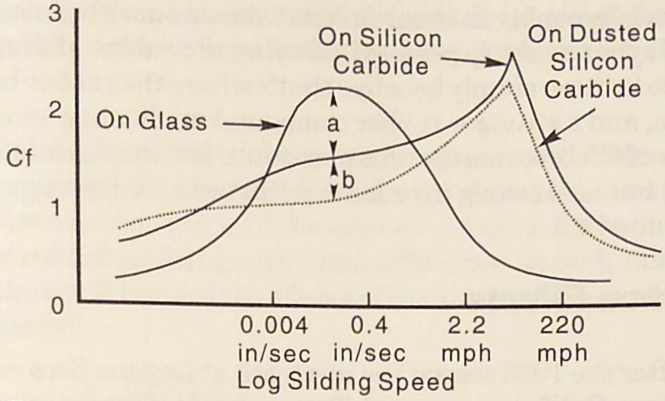

Fig. 3.8 Speed Sensitivity of Friction Components

The dotted curve is data taken with the rubber sliding on sandpaper dusted with finely powdered magnesia, which eliminates adhesion by preventing contact between the rubber and the surface. The distance "b" then represents the Fad lost at that sliding speed by lubricating the rough surface.

Notice that "b" is the maximum difference between the dusted and undusted curves on sandpaper at any speed and that "b" occurs at a sliding speed where this rubber exhibits maximum C_f on glass. This tells us that Fad exists on a rough surface also, and peaks at the same sliding speed as it does on glass. We learned in the previous section that adhesion friction contains viscoelastic characteristics similar to deformation friction, so it should not be a surprise they both peak at the same sliding speed.

Maybe we can sum all this up by confirming that rubber friction is indeed a combination of discreet components. The same rubber compound sliding on smooth glass and also on a rough surface generates friction forces mainly by surface adhesion but also by absorbing deformation energy. Both the adhesive and deformation components of friction exhibit viscoelastic effects, making them sensitive to sliding speed, and both are influenced by hysteresis, internal damping in the rubber. Fdef looks to be more sensitive to sliding speed because of the sharp peak in Cf on sandpaper. Or does that sharp peak have another cause?

Notice the data taken on sandpaper peaks at a C_f of almost 2.5. The curve is rising and then falls off sharply. If viscoelastic effects in rubber are speed sensitive, you'd expect that curve to continue to rise with increasing sliding speed. Experimenters have noted that a smear

of rubber on the glass is a common occurrence when taking data during this type of test. This suggests that the maximum frictional forces might depend to some degree on the tensile strength of the bulk rubber sample. Under conditions that produce max C_f the rubber surface is probably in shear failure even on smooth glass.

Maybe the sharp peak exhibited by the rubber sliding on a rough surface is there simply because that's where the rubber begins to abrade, and a stronger rubber compound might show us even higher values of Cf. It seems that for maximum friction forces a rubber has to be soft but also strong in order to withstand the forces generated at maximum Cf.

Road Surface Effects

After the 1996 season the racetrack at Laguna Seca near Monterey, Calif., was repaved. Testing by CART teams the next spring revealed much higher levels of grip and lap times dropped by seconds from those of previous events. But when the teams returned for their race at Laguna the following September, they found much lower grip levels and had to drastically change the setups they had so carefully developed six months earlier. During that race weekend I remember a couple of people attributing the problem to pavement wear, but didn't understand the phenomenon until I began to write these chapters.

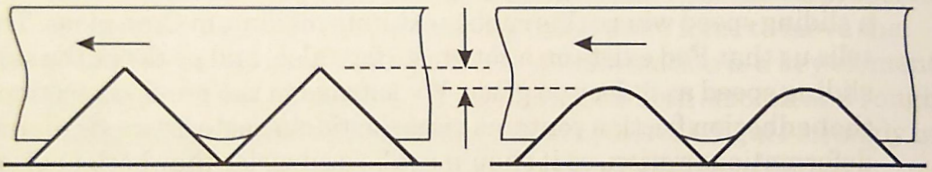

Fig. 3.9 Effect of Surface Wear on Grip

As depicted in Fig. 3.9, fresh pavement has sharp rocks sticking up through the asphalt matrix, and that's what the CART teams experienced at Laguna Seca immediately after the repaving. The high levels of grip allowed record-low lap times. But during the next six months the Russell Driving School cars and racecars competing in the many SCCA and vintage events polished off the sharp corners of the aggregate.

Here's another story illustrating the benefits of fresh pavement. At the Indy 500 several years ago, Roberto Guerrero was having trouble qualifying. He's famous for a high line, not clipping the apex low in the corners. His team sought outside help and someone pointed out to

them that there were fresh asphalt patches low in the corners. Guerrero moved his line down onto the new pavement and made it into the show.

Fig. 3.9 shows that wearing of the aggregate both lowers and rounds the peaks on the individual stones. It turns out that the shape and texture of road irregularities makes a difference.

Shape

We know now that rubber friction is a combination of different forces, mainly adhesive and deformation. Adhesive forces increase with contact area and load. Deformation forces, however, come from sliding rubber creating a pressure difference on each side of a road irregularity. What are the effects of the size and shape of the road irregularity?

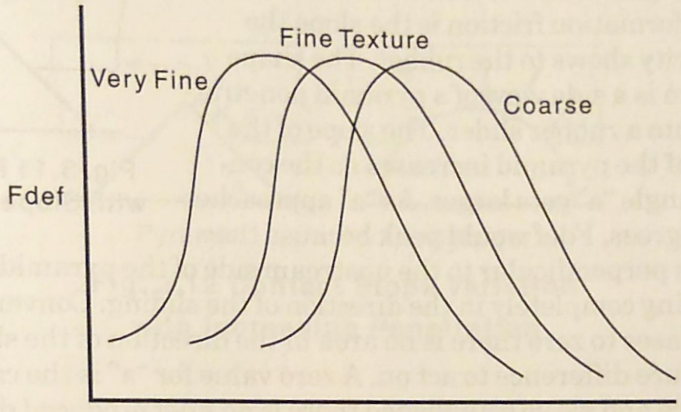

Fig. 3.10 Surface Texture Effects on Rubber Friction

Fig. 3.10 shows Fdef, the friction coefficient caused by deformation, plotted against the logarithm of sliding speed for several road surface textures. The coarse texture was formed by round shapes of about 0.25 inches in diameter. The fine texture was one hundredth that size, or 0.0025 inches and the very fine texture approximated 0.00025 inches in diameter. Since all three textures produce the same level of Fdef, we have to conclude that asperity size doesn't matter.

Notice, however, that the peaks are at different sliding speeds. Fdef is speed sensitive as you would expect of a viscoelastic effect. The rubber sees smaller, higher-frequency deformations as the surface textures get finer. So, for each texture there is an optimum sliding speed at which rubber friction is at a maximum for that texture.

This graph suggests an important point about road texture. If a racetrack surface contains a broad range of aggregate sizes, the sliding-speed peak will be broad, because all three of these curves

would be in force. But if the pavement contains aggregate made up of material all about the same size, grip might be at a maximum for a very small range of sliding speed. And what if the stones in the pavement were either coarse or fine, with nothing in between? In that case you might have a grip peak at low and high sliding speeds but less grip at speeds in between the two extremes.

I think this is one of the reasons why concrete patches sometimes produce less grip than the surrounding asphalt paving. The sand aggregate in the concrete is smaller than the stones in the asphalt, so its optimum sliding speed is different. The sand is also roughly the same size throughout the patch, so it has a small range of sliding speed over which it would produce maximum grip.

Slope of the Asperities

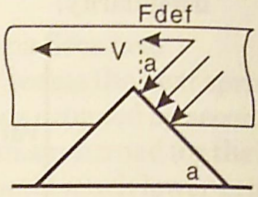

Fig. 3.11 Fdef Varies with Slope of Asperity

Fig. 3.11 shows that what does matter in deformation friction is the slope the asperity shows to the rubber. The shape shown is a side view of a pyramid penetrating into a rubber slider. The slope of the side of the pyramid increases as the contact angle "a" gets larger. As "a" approaches 90 degrees, Fdef would peak because the forces perpendicular to the upstream side of the pyramid would be pointing completely in the direction of the sliding. Conversely as "a" decreases to zero there is no area in the direction of the sliding for the pressure difference to act on. A zero value for "a" is the case of a flat surface and we've established there is no Fdef produced during sliding on a flat surface.

Fig. 3.12 shows how asperity slope varies with penetration for two shapes, a pyramid and a cylinder. The rubber sees a surface at the same angle as it penetrates into the pyramidal asperities. Deformation friction would increase at a constant rate as penetration increases.

But a cylindrical shape is different. The contact angle starts near zero at light penetration and increases. With no surface perpendicular to the sliding rubber, a lightly penetrating cylindrical asperity would generate very little deformation friction. But Fdef increases rapidly with penetration as the contact angle increases.

These effects are summarized in Fig. 3.13. Contact stress is the force per unit area pressing the two shapes into the rubber. As you can see both schematically and graphically, the pyramid shape presents an unchanging slope to the rubber. But, with the cylinder, the rubber sees a very low slope on initial contact and Fdef increases with penetration.

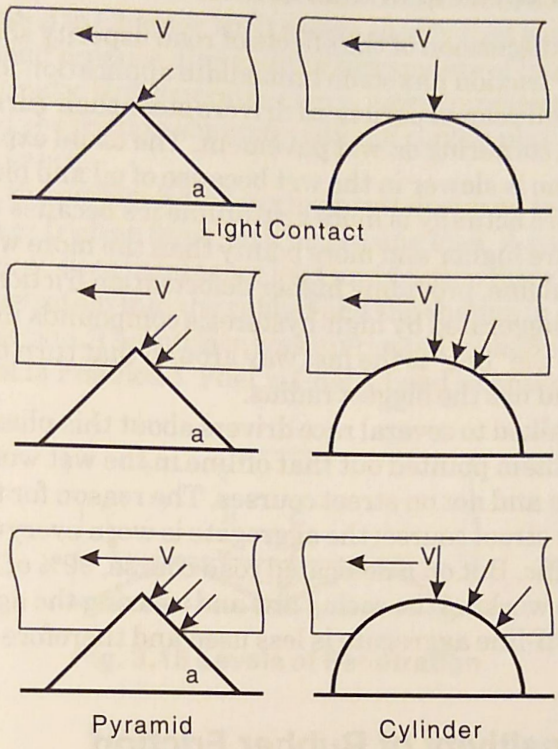

Fig. 3.12 Contact Slope Variation with Increasing Penetration

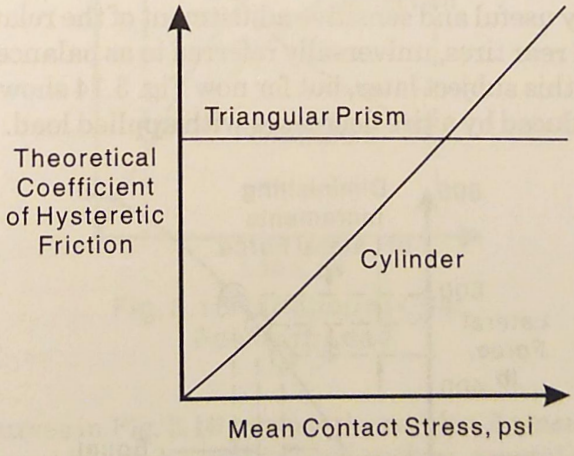

Fig. 3.13 Shape and Load Effects

The Myth of Off-Line in the Rain

This discussion of the effects of road asperity shape and texture on rubber friction has some immediate application for racers. We've probably all seen experienced drivers steer their cars off the normal line when cornering on wet pavement. The usual explanation is the normal line is slower in the wet because of oil and old rubber.

If there actually is more grip offline it's because the surface features are higher and more pointy than the more worn features on the normal line, providing higher deformation friction. This phenomenon is exaggerated by high-hysteresis compounds in racing rain tires. When dry the "line" is the fast way around that turn because it's shorter and has the biggest radius.

I've talked to several race drivers about this phenomenon and a couple of them pointed out that offline in the wet worked on dedicated racetracks and not on street courses. The reason for that is there is no "line" on a street course; the aggregate is worn everywhere by daily street traffic. But on a dedicated road course, 99% of the cars on the course are working the racing line and wearing the aggregate in the process. Off-line aggregate is less used and therefore more coarse and pointed.

The Load Sensitivity of Rubber Friction

Almost all racecar setup adjustments exploit the load sensitivity of tires. An adjustable anti-roll bar (ARB) on a racecar manipulates lateral force transfer across the front and rear tire pairs, making an extremely useful and sensitive adjustment of the relative grip of the front and rear tires, universally referred to as balance. You'll see more detail on this subject later, but for now Fig. 3.14 shows how the lateral force produced by a tire decreases with applied load.

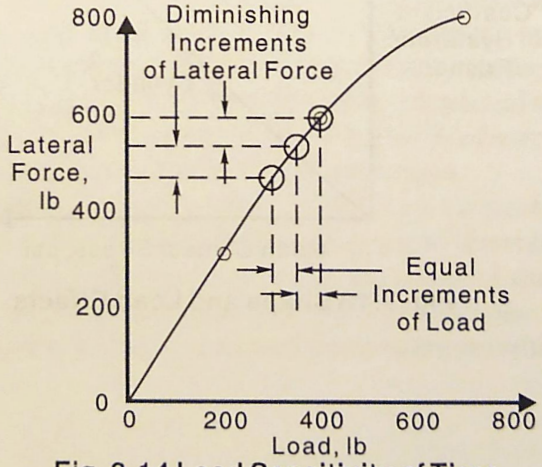

Fig. 3.14 Load Sensitivity of Tires

This graph of lateral force vs. load comes from actual race tire data presented in Chapter 10. It shows clearly that equal increments of increased load produce diminishing increments of lateral force. The way a pneumatic tire generates grip is more complex than rubber friction, but the friction characteristics of rubber play a large part in tire performance.

Fig. 3.15 and Fig. 3.16 describe a test designed to show us why rubber looses friction force with increasing load. A rubber slider at some speed, V, sees increasing load and friction force is measured as well as penetration into the rubber and the change in slider thickness, called deflection. The surface was lubricated to discourage adhesive forces. Cdef is Fdef/load. Fdef is Cdef x Load x contact area.

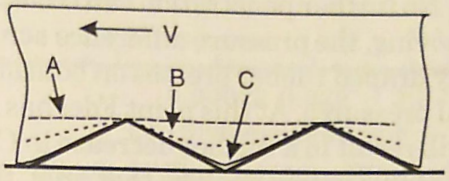

Fig. 3.15 Levels of Penetration

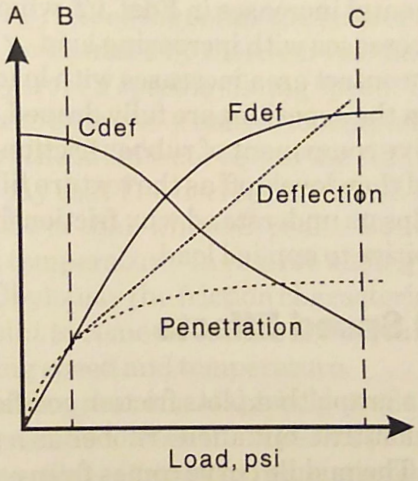

Fig. 3.16 Variation of Cdef, Fdef with Load

The curves in Fig. 3.16 present the results. As increasing load presses the rubber slider into a rough surface, several important factors change. The line at "A" represents a very light load on the slider. The dotted line "A" in Fig. 3.15 is just touching the tops of the surface irregularities. Under this light load Cdef is high and Fdef increases in a straight line. Both the distance the asperities penetrate

into the rubber and contact area are increasing with rising load under this light-load condition. Since Fdef increases in a straight line with increasing load there is no load sensitivity up to line B.

As more load presses the rubber slider farther into the asperities there is a loading condition at line B when Cdef falls off, and penetration falls off. The asperities have penetrated into the slider and further penetration slows as elastic forces in the rubber resist movement. The curves of deflection and penetration diverge. This indicates that, at this load level, higher loading causes the asperities, which are now almost fully draped with rubber, to begin to deflect the entire surface of the rubber instead of penetrating further into it.

When increased load on the slider presses the rubber into the asperities such that the rubber fills the texture completely, condition "C" is reached. No further penetration can occur, and even though the slider is still moving, the pressure difference across each asperity is small. The fully draped rubber presses on both sides of the asperities at almost equal pressures. At this point Fdef has leveled off and increased load will result in a further decrease in Cdef.

The result of this data is to show that Fdef, the deformation component of rubber friction, rises with increasing load but at a decreasing rate. Increasing from light load to higher load results in smaller incremental increases in Fdef. Cf, which is Fdef divided by the applied load, decreases with increasing load.

Given that contact area increases with load and then reaches a maximum when the asperities are fully draped, we can assume that Fad, the adhesive component of rubber friction, also increases with penetration and then levels off as the texture fills with rubber. All this information helps us understand why friction forces due to sliding rubber are sensitive to applied load.

Temperature and Speed Effects

Fig. 3.17 is a graph that plots friction coefficient vs. the sliding speed of an acrylonitrile-butadiene rubber on a glass surface where Fad dominates. The middle curve comes from experimental data and the other two curves were generated using an observed relationship between the so-called glass transition temperature of an elastomer and the temperature at which it exhibits maximum C_f.

The numbers at the peaks of these curves are the glass transition temperatures (T_g) for that particular rubber. As an elastomer (remember rubber is an elastomer, a viscoelastomer) cools to its T_g, a sort of phase change happens and its modulus (stiffness) and viscosity go up sharply over a small range of temperature. The flexible, long-chain molecules loose some mobility and the material behaves more like a glass than a rubber.

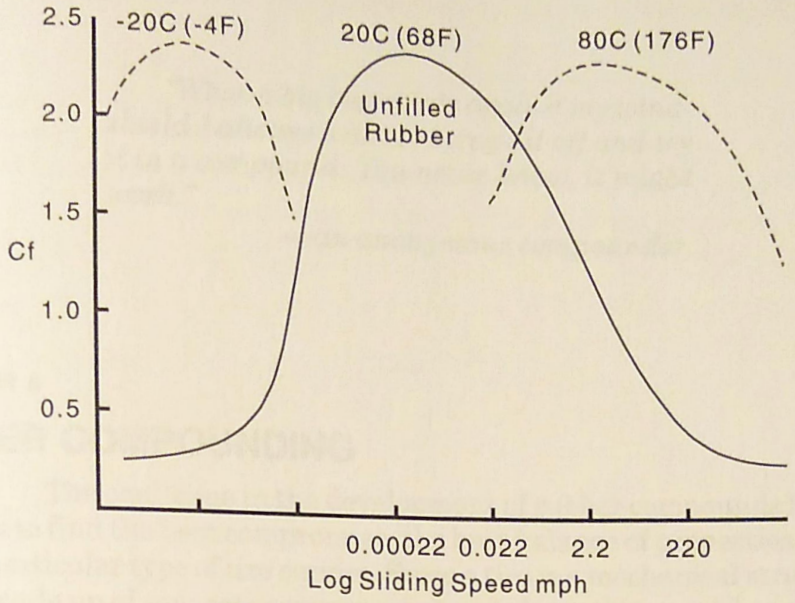

Fig. 3.17 Temperature Effects

Basically the bigger the difference between T_g and the operating temperature of the rubber the softer the rubber becomes and the more grip it develops. You can see by these curves that these rubbers fall off in C_f very quickly from a specific sliding speed. This is probably the main reason that tires are so sensitive to temperature.

If you look at the middle curve and the sliding speed at which it peaks you could say that Fad decreases with sliding speeds that are either higher or lower than where C_f peaks. But this data was generated at constant temperature. In real life sliding produces heat, which increases Fad. Obviously the friction characteristics of rubber are complex. The point to remember here is that rubber friction is very sensitive to sliding speed and temperature.

I'm just guessing, but one of the holy grails of race tire compounding has to be to create a rubber that operates at a temperature as far above its T_g as possible. But softer is not stronger. So ways have to be found to keep the softer rubber from pulling apart with stress at a high temperature. And to complicate things, that compound on that tire has to reach and maintain the optimum temperature on a specific racecar at a specific racetrack under the particular ambient conditions of a specific race day.

But we're getting ahead of ourselves. Let's take a look at what makes up a real-life tire compound.

"When a big bug splats against my windshield I always want to scrape it off and try it in a compound. You never know, it might work."

—an anonymous compounder.

CHAPTER 4

RUBBER COMPOUNDING

The challenge in the development of rubber compounds for tires is to find the best compromise, the best balance of properties, for a particular type of tire service. Since a tire is a mechanical structure made up of separate components bonded together, a rubber component has to be judged on how it functions in the system—in a tire—rather than on its individual properties or performance capabilities.

For example, a rubber compound that does not adhere well to other tire components or requires different vulcanization conditions than other parts of the tire can be useless even though it has superior performance as an individual component. But how does a tire designer know how well a specific compound bonds to other components without actually building some tires with that compound? For that and other reasons tire development is not highly analytical but is the result of skill and experience and trial and error.

Tread compounds have conflicting requirements. They must provide wear resistance but also be tough and resilient so as to minimize cuts, tears, and cracks. Low-hysteresis rubber in the tread is desirable for less rolling resistance and low operating temperatures in road-car tires. But high-hysteresis rubber is better for racing applications. Rubber used in the tire structure or carcass must form strong bonds with the adhesive-coated cords and be strong enough to hold them in place and protect them. But the rubber must be soft enough to let the cords move as the tires flex. Compromise and optimization are the watchwords of the compounding engineer.

Which Rubber?

The first choice a tire designer makes is what rubber to use as the principal polymer material in the tread. The tread makes contact with the road surface and does the work critical to the tire's performance in a specific application. Obviously the rubber compound used in tires for long-haul trucks is different than that used in a racing rain tire.

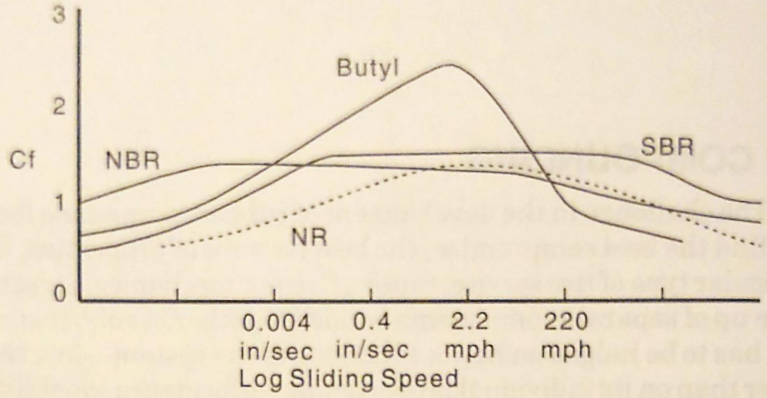

Fig. 4.1 Friction Characteristics of Rubbers

Fig. 4.1 presents friction coefficient (C_f) data taken on sandpaper using several different rubber polymers: NBR is acrylonitrile gum rubber, NR is natural rubber, Butyl is polyisobutylene, and SBR is styrene butadiene. For this test these rubbers had 50 parts per hundred of HAF carbon black. More about carbon black later. The point of this graph is to show the wide range of C_f vs. sliding speed exhibited by these four different rubbers. If max C_f was the only criteria for the rubber in a particular compound, the choice would be easy.

The table below presents data from braking tests using tires with treads of several different rubber compounds. Two additional pieces of data appear. Rebound is a simple test for hysteresis in rubber described in the last chapter. A higher hysteresis rubber rebounds less than a lower hysteresis rubber. Hardness in this case is a durometer reading which measures the penetration of a stylus into a rubber sample. A harder rubber gives a higher durometer number.

Table 4-1: Observed Stopping Distance on a Wet Asphalt Road

Rubber	Rebound %	Hardness	Stopping Distance, ft
BR	62	62	180
NR/BR	46	57	163
EPDM	32	63	160
SBR/BR	33	55	158
SBR	34	52	151
Butyl	9	40	130

The table shows that a short stopping distance requires a soft, high-hysteresis rubber. Simply stated, anything you can do to a rubber compound to raise its hysteresis and lower its hardness will decrease the stopping distance (increase the grip) of a tire using that compound. But a successful tread compound requires a complicated series of compromises. Unfortunately a soft, high-hysteresis rubber is highly skid resistance but wears rapidly, so the most difficult qualities to obtain simultaneously are high skid resistance and high wear resistance.

Recipe for a Tire

Ingredients in tire compounds can be classified as: 1) rubber, a single polymer or a blend of polymers with a high molecular weight; 2) extending oil; 3) filler systems, blends of various carbon blacks, silicas, or newer alternate filler materials; 4) small amounts of processing aids such as softeners, plasticizers, or reclaimed rubber; 5) the chemical vulcanization system which is likely to include two accelerators, sulfur and zinc oxide; and 6) other chemicals such as antioxidants and antizonants.

With such a wide variety of ingredients, the important mechanical properties for a given tire compound can be obtained from a number of different compositions. For example, modulus (stiffness) and hardness can be controlled by varying either the amount of carbon black, the amount of extender oil or softener, the fineness or structure of the black, or the number of molecular crosslinks introduced during vulcanization. For this reason even small advantages in cost, performance, and processing, which may only become apparent with extensive testing or service experience, become important factors in compound selection. No tire compound is ever judged as ultimate perfection but is continually improved as test results and experience accumulate.

The following table represents four very generic recipes for rubber that might be used in tire tread. There are two types of SBR—a synthetic rubber, a styrene-butadiene copolymer—listed in the ingredients. Three types of carbon black are used. EPC stands for Easy Processing Channel black, HAFF for low-structure High Abrasion

Furnace black, HAF for High Abrasion Furnace black, and FF for Fine Furnace black. Quantities shown are "parts" determining relative amounts of the total mix compared to 100 parts of the polymer.

Table 4-2: Generic Tread Rubbers

	Compound			
	A	B	C	D
Ingredient, parts				
SBR 1000	100	100		
SBR 1500			100	100
Black, EPC	50			
Black, HAFF		50		
Black, HAF			50	50
Softener	8	8	5	5
Antioxidant	1			
Zinc oxide	3			
Stearic acid	1.5			
Sulfur	1.75	1.75	1.75	2.0
Accelerator 1	1.25	1.00	0.80	
Accelerator 2				.080
Cure: 50-60 min. @ 292 F.				
Tensile strength, psi	2290	2230	3810	3750
Elongation, %	520	490	510	515

Oils, called softeners in the table, are an important component in the rubber used in tires. Many kinds of oils are used, imparting very different properties to the finished product.

The chemical element sulfur forms the bonds between rubber chain molecules, changing the uncured rubber from Charles Goodyear's stinky, sticky mess into a stable, highly useful material. Chemicals called accelerants and curing agents help tune the rate of bonding. Tires work if the mix of all this stuff is vulcanized correctly—put together with just the right heat and pressure for just the right amount of cooking time during the vulcanization process.

Carbon Black Reinforcement

Carbon black, soot to us non-rubber people, is a major component of tires. The carbon black/rubber system is extremely complex and has not been completely characteriszed. The details of what is known is deemed proprietary by tire manufacturers, so the following is well-known, generic information.

During compounding, carbon black particles are mixed with rubbers and other ingredients in machines that work the mixture with high shear forces. One of the machines used looks like a gigantic taffy puller and is called a Banbury mixer.

The carbon particles tend to form a loose network structure because of their surface activity and mutual attractions. The cross-linked rubber molecules become interlaced into the carbon structure. The carbon black particles are very fine and their surface area is chemically active enough to form additional crosslinks. As a result carbon-black filler greatly increases the viscous forces on the chain segments of the rubber molecules as they move to accommodate external forces.

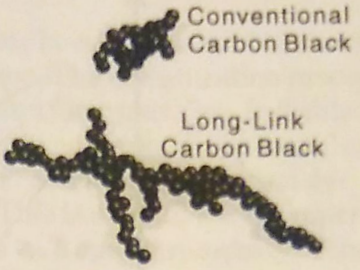

Fig. 4.2 Carbon Black Structures

Almost all fillers used in rubber goods manufacturing increase the modulus or hardness, but carbon black also significantly improves tensile strength, tear strength, and road wear properties. Carbon black also enhances viscoelastic (VE) effects so mechanical energy losses due to hysteresis increase. The overall effect of increasing carbon black is higher strength and increasing VE effects. Higher strength is probably due to interbonded particles preventing the growth of tear failures among polymer chains.

There are many varieties of carbon blacks, each imparting different characteristics to a rubber compound. Particle size and physical properties of the surface are important characteristics of carbon blacks. No one type of black can be called optimum for a tire. Fig. 4.2 shows a type of carbon black used in Bridgestone-branded street tires. Called L.L. (long link) Carbon, this black forms longer chains for better reinforcement of the rubber and is used in a Bridgestone tread compound along with a silica filler and SBR rubber.

Fig. 4.3 shows the effect of increasing amounts of carbon black on several important properties of rubber used in tires. The vertical axis of the graph represents an increase in each of the measured properties named in the graph:

Tensile strength: a measure of the ultimate strength of a material—the force required to break a sample when it is pulled from both ends. The data is usually presented as the force per square inch of cross-sectional area of the sample used in the test.

Breaking elongation: during a tensile-strength test the sample stretches before breaking and this data presents the amount of stretch in percent.

Pendulum rebound: also described in the previous chapter, this test is a measure of hysteresis in rubber and is used for in-process quality control. Immediately after a batch of ingredients has been processed according to manufacturing procedures, a small piece of

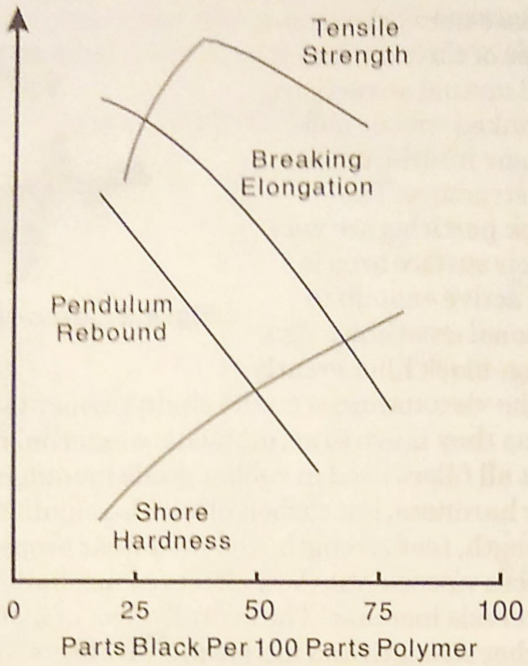

Fig. 4.3 Carbon Black Loading Effects

this new rubber compound is cut off and sent to a test lab where a test sample is prepared, again according to written procedures. A weight on a string is released from a fixed height to impact on a piece of the test rubber. The rebound distance as a percent of the total drop distance is an indication of hysteresis, or energy absorption. Less rebound is increasing hysteresis.

Shore hardness: A specific measuring device called a Shore Hardness Tester uses a spring to press a probe of a specific size into a sample. A higher number indicates a harder material.

The results of these tests as shown in Fig. 4.3 are important because: 1) increasing black improves tensile strength to a point and falls off; 2) as the rubber gets stronger it stretches less before it breaks; 3) more black makes the rubber harder, and 4) increasing amounts of black enhance hysteresis..

Silica is another filler used in both road and race tires. Essentially silicon oxide, one of the most abundant materials on earth, SiO2 is also used in making common glass. Silica is not electrically conductive as is carbon black, and early tires made with silica in place of black exhibited a problem with build-up of static electrical charge during use.

Silica reduces rolling resistance and expands the useful temperature range above the compound's glass transition temperature. Tread compound containing silica/carbon black ratios of from 25/75 to 50/50 produce better tread wear and better wet traction.

Vulcanization

Fig. 4.4 presents generic data showing how various rubber characteristics vary with increasing vulcanization. The vulcanization process creates links among polymer molecules and filler particles. In Table 4.2 this particular recipe for a rubber compound specifies a "cure" of 50 to 60 minutes at 292 degrees F. Rubber compounds are often described as "undercured" or "overcured." This is a relative term generally referring to the time at temperature vs. a specific property of the desired compound. For example, a specific compound might be overcured to decrease hysteresis in the final product or undercured to make it turn out softer.

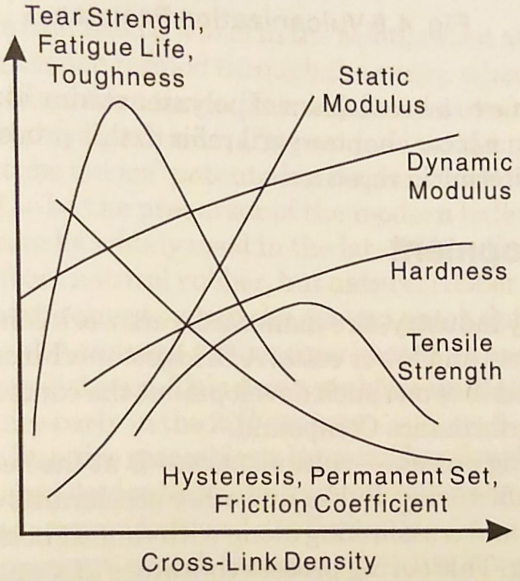

Fig. 4.4 The Effects of Vulcanization

Fig. 4.5 is a graph of modulus (stiffness) vs. time, describing an ideal vulcanization process. The raw materials for the compound go into a mixing machine and heat is added during mixing to start the vulcanization process, which then continues on its own for days. When cross-linking begins the mixture stiffens and various methods are used to monitor the process by measuring the viscosity of the mixture. Even after a tire is removed from a mold and cools, the vulcanization process continues and tire properties improve.

If the vulcanization process goes too far, the mix is overcured. The rubber looses strength and becomes soft and tacky and is said to have reverted to an uncured state. Reversion is the loss of network

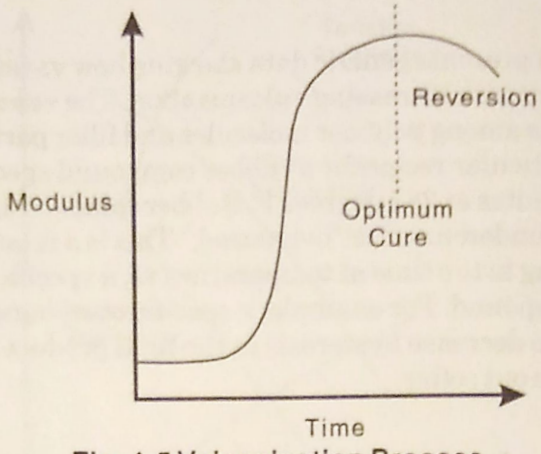

Fig. 4.5 Vulcanization Process

structures due to a breakdown of polymer chains and destruction of crosslinks. In a later chapter we'll refer to this process when discussing tread blistering in racetires.

Additive Development

As in any industry, tire manufacturers work continually to develop better products and lower costs. A Bridgestone/Firestone technology brochure describes one such development the company calls EPC, or Extended Performance Compound.

The curing process—vulcanization—is at the heart of tire and rubber manufacturing. Sulfur and other accelerants encourage polymer bonding and crosslinking along with time at heat and pressure during curing. This curing process continues at a much slower rate at the relatively low ambient temperatures seen by a tire in service. But a tire tread does see localized heat, pressure, and mechanical stress in use and these conditions can cause the sulfur to continue to enable polymer bonds and crosslinks. This can increase rubber hardness, decreasing flexibility and hysteresis.

We know now that rubber generates higher friction forces when it's more flexible and has higher hysteresis. This is especially so in wet-road conditions when much of the available adhesion goes away, leaving the deformation friction component to generate traction force. Bridgestone/Firestone's EPC compound contains an additive that suppresses sulfur crosslinking in service, preventing the deterioration of wet grip during the active life of the tire.

We can guess that if there is an additive to suppress bonding and crosslinking there are additives that encourage this process. We'll speculate about that topic in the chapter on race tires.

"We have a system and it works."
—Mr. Carpenter, the alien visitor in the movie "The Day The Earth Stood Still."

CHAPTER 5

TIRE DESIGN AND MANUFACTURE

Humans first used a wheel in the Middle East about 5,000 years ago. Although much refined through the years, wheels remained primitive until modern times. The major negatives being poor traction, an uncomfortably harsh ride, and poor load-carrying capacity.

An "air tube device" patented in England by R. W. Thomson in 1846 proved to be the precursor of the modern balloon tire. This device began to be widely used in the late 1800s. Early tires were solid tubes made from natural rubber, but natural rubber is high in hysteresis and absorbs energy when the contact patch deforms as the tire rolls. These solid, natural-rubber tires heated up and melted after rolling a short distance. This was a problem until the development of the balloon tire early in the 20th century.

Physically a tire resembles a large rubber doughnut, but actually it is a complicated device to design and manufacture. Geometrically a tire is a torus wrapped around a cylinder. Mechanically it is a flexible-membrane pressure vessel. Structurally a tire is a composite of steel wire and high-strength textiles in a rubber matrix. Chemically a tire consists of viscoelastic rubber polymers reinforced with carbon black or silica, textiles woven from high-strength polymer fibers, steel wire, and several different types of adhesives. The final manufacturing process cooks an assembled tire for a certain time at a specific temperature and pressure to vulcanize the rubber and bond the components into a unified structure with the desired material properties.

Structure of the Pneumatic Tire

Tires are required to satisfy conflicting requirements. They need to be flexible so they can absorb road irregularities but stiff enough to generate cornering forces and maintain straight-line motion with an unchanging rolling radius. A tire's internal pressure dictates a curved cross section, but the contact patch must deform under load to give a flat area of contact on a road surface.

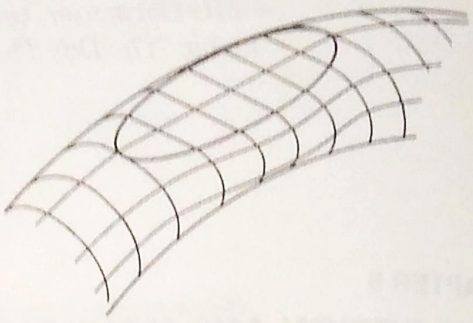

Fig. 5.1 Flat Contact Patch on a Torodial Shell

Two possible configurations exist for tire design: a solid tire made from a soft, highly elastic material or a gas-inflated envelope coated with a soft material that has good traction. No one has developed a practical solid tire yet, so the current design is a pressurized, hollow, composite structure made of flexible filaments of a high-modulus material—textile, metal, or glass fiber—bonded to a low modulus rubber matrix.

Modulus of Elasticity

We need to define modulus because we're going to use the term often. The correct term is modulus of elasticity and it's a measure of a material's stiffness. Any material of any shape will deform if you push on it hard enough. How much it deforms in response to a specific load is a measure of its elasticity. We call the applied load "stress" and the resulting deformation "strain." The relationship between stress and strain is described by the following equation:

Modulus of elasticity = K = Stress / Strain

Stress is the applied load in pounds divided by the area over which the load is applied to the sample. Strain is defined as the ratio of the change in size or shape to the original size or shape. Since the strain number has no dimensions, modulus has the dimensions of stress—pounds force per unit of area.

Example: a 10-in. long cylindrical sample of a material one square inch in cross-sectional area is pulled in tension with 1,000 pounds of force. That applies a stress of 1,000 pounds per square inch (psi) to the sample.

If the applied stress stretches the 10-in. sample a tenth of an inch, the strain is 0.1 inch divided by 10 inches (the original length) or 0.01. So K is 1,000 psi divided by 0.01, or 100,000 psi.

Table 5-1: Typical Values for Modulus of Elasticity

Material	Modulus, psi
Steel	29,000,000
Aluminum	10,000,000
Glass	8,700,000
Epoxy	500,000
Rubber, unreinforced	150
Rubber, textile body ply	800
Rubber, textile tread ply	3,000
Rubber, steel tread ply	2,000

You can see from this table that rubber has a very low modulus compared with other materials. Later in this chapter we'll see that the textiles used in tire construction are much stiffer than the rubber, which causes special problems and solutions.

Fatigue Strength

Another concept we need to recognize is fatigue strength. Fatigue is the most common cause of material failures. A common coat hanger is made from an inexpensive steel wire, and although none of us can pull coat-hanger wire apart we can actually break the wire if we take advantage of the poor fatigue resistance of this particular material.

You need to grasp the wire with the fingers of both hands and bend it back and forth through as large an arc as possible. Make sure you're bending the wire at the same place, but in different directions. If you do this quickly you'll feel the wire heat up where it's bending and then it will break. In materials engineering terms you have subjected the wire to cyclic stress and exceeded its fatigue strength.

The first high-altitude jet airliners crashed for mysterious reasons. Then a meticulous engineer speculated the cause was fatigue in the aluminum sheet metal of the fuselage. Aircraft structures are pressurized so passengers and crew can survive at high altitudes. The structure expands like a balloon as the plane climbs to cruising altitude and shrinks back to normal size when it lands. Several of these stress/strain cycles per day over a period of years add up, and cracks begin to form just as they did when you cycled the coat-hanger wire.

To confirm that metal fatigue was the problem, an aircraft fuselage was subjected to pressure cycles under water. Testing raised and lowered the internal pressure inside the fuselage time after time. Bubbles appeared after a high number of cycles, pinpointing areas of

failure. Cracks developed in highly stressed areas around the windows. Since then aircraft designers are careful to use double- and triple-thickness material in those areas.

Fatigue strength is also extremely important in tire design because tires are stressed cyclically. The shape of a tire is distorted in the contact patch, and as the tire rotates, the cords are forced to bend both coming into and going out of the contact patch. This bending causes heat build-up in the rubber due to hysteresis and can create a fatigue failure at the cords/rubber interface. Fortunately hysteretic losses in rubber decrease as temperature increases. If hysteretic loss rose with increasing temperature the system would be unstable.

Fatigue Failure

Following a small initial point of failure, a separation somewhere in the cord/adhesive/rubber system, there will be increased relative motion between the cord and rubber and among the cord filaments themselves. Mechanical working of the filaments leads to failure of individual filaments and then to total cord failure. Mechanical working can also propagate any cord-to-rubber adhesive failure that occurs. Testing shows that the cord failure process, once initiated, can run a rapid course to complete tire failure similar to the effects found in propagation of a fatigue crack in metals.

Of course the solution to the fatigue problem is the design and manufacture of a product with sufficient fatigue strength. The basic design of the tire and the manufacturing processes used to build it must be carefully specified according to the service environment and length of service life of the tire.

Tire Design

The stiffness and strength behavior of textiles and rubber have each been studied in detail and their characteristics are well known as they apply to tires. The low-modulus, high-elongation rubber contains the air and provides abrasion resistance and road grip. The high-modulus, low-elongation cords provide reinforcement for the rubber and carry most of the loads borne by the tire. The material properties, however, of the cord/rubber composite is difficult to analyze and it doesn't help that the elastic properties of this system—whether you call them stiffness, compliance, or modulus—are anisotropic.

Anisotropy is a weird name for something that's familiar to all of us. Anyone who's ever played baseball has been taught to hit a ball with the bat label facing up. That's because the label is always burnt into the wood parallel to the grain of that piece of wood, and wood is stronger parallel to the grain than when the wood is turned 90 degrees.

A pack of playing cards is another example. A stack of cards bends easily with some force applied on the wide dimension, but is stiff if the cards are on edge.

A sheet of rubber reinforced with textile cords is pretty floppy until it's formed into a tube and stiffened with internal gas pressure. A tire can be strong but only if it's inflated.

A tire has to fit on a wheel and be easily installed on and removed from that wheel. This is not a trivial requirement. The final solution, a close-fitting tire/wheel design, didn't become common until the mid-20th century.

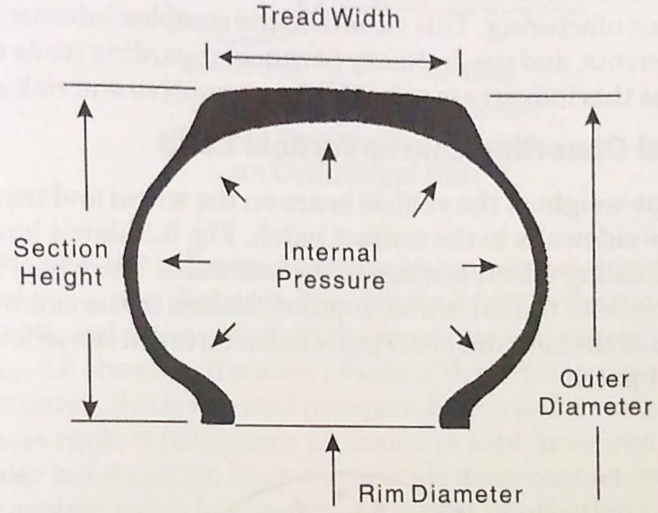

Fig. 5.2 Load-Capacity Variables

Fig. 5.2 shows a cross-section of a mounted tire and the important dimensions. In general the load-bearing capability of a tire is proportional to the internal pressure, the diameter of the wheel rim, tread width, and the section height of the tire.

Contact Patch Load Effects

Fatigue strength of the tire cords, internal pressure, vehicle speed, time spent at that speed, load on the tire, and length of the contact patch are the critical specifications for a tire. The tire designer must choose the best compromise among many choices of materials, cord angles, and manufacturing processes in order to create a tire with the performance and durability required for a specific application. And the manufacturing cost has to be low enough for the product to be profitable.

Those design specifications listed above—internal pressure, the diameter of the wheel rim, tread width, and section height—determine the size of the contact patch of a tire at a given vertical load. The internal pressure in the tire actually supports the vertical load bearing

on the tire through the contact patch. From the tire's point of view there is a distortion pattern rotating around the tire as it rolls. This flexing in the tire structure creates heat due to the internal damping in the rubber. This flexing can also cause fatigue failures in the structure and fatigue failure is the main concern of the tire designer.

Making the design choices even more important is the fact pointed out in the introduction to these chapters on tires, that a tire failure can be difficult to predict or analyze. That's because, after the final molding and vulcanization, a tire is a bonded unit that can't be disassembled without destroying that tire. When you can't easily dissect a failed product you don't want to take any chances in design and manufacturing. This situation, the complex interaction of tire components, and tire-industry paranoia regarding trade secrets are the reasons this industry is so heavily conservative and risk adverse.

Structural Distortion Due to Vertical Load

The weight of the vehicle bears on the wheel and travels through the tire sidewalls to the contact patch. Fig. 5.3 shows how contact patch loading affects tension in the sidewalls. The wheel is literally hanging from the sidewalls, creating tension in the sidewall cords at the top of the tire and lowering tension forces in the sidewall near the contact patch.

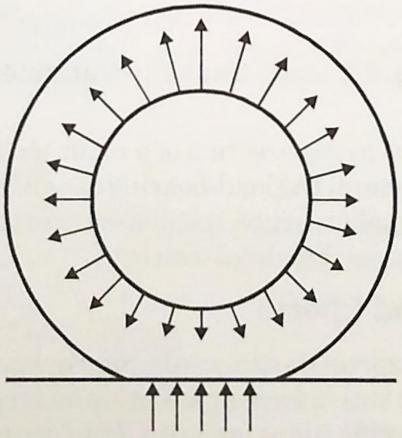

Fig. 5.3 Sidewall Differential Tension Due to Contact-Patch Load

Fig. 5.4 presents two views of a torodial membrane on a cylinder and shows how the sidewalls change shape with load. A tire's sidewall cords are in tension due to internal pressure and external loads. That tension would be equal in all the sidewall cords of an unloaded tire.

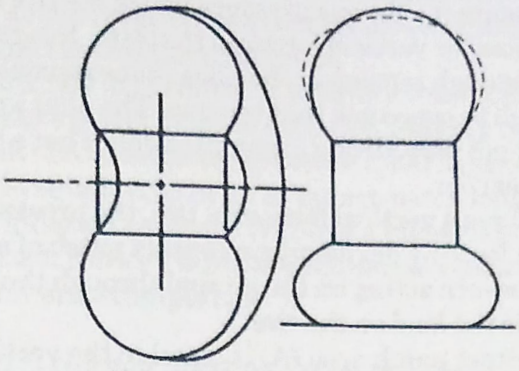

Fig. 5.4 Torodial Membrane on Cylindrical Rim

When a tire is loaded vertically the contact patch distorts, lowering internal volume in that area. The sidewalls not in the contact patch segment round out to maintain the same internal volume in the tire.

Fig. 5.5 shows still another mode of distortion caused by a loaded contact patch. Since internal pressure supports the vertical load on a tire, more contact patch area is needed as load increases. The CP can't get wider but it can get longer to provide more contact area. But a longer contact patch has several important implications. We'll discover one of those now.

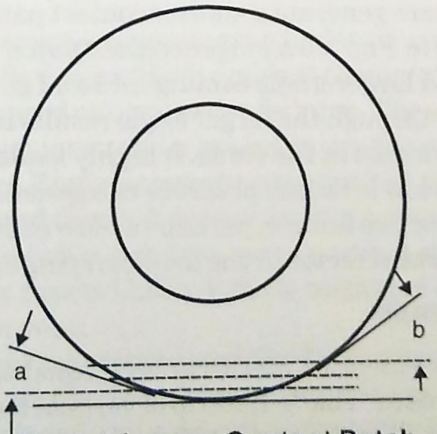

Fig. 5.5 Longer Contact Patch Bends Through Larger Angle

Load and Internal Pressure

Once again it's the gas pressure inside the tire that supports the weight (or load or vertical force) on that tire. Internal pressure also generates enough tension in the plies that external forces are never large enough to overcome that tension. The plies are very strong in tension but not very strong in compression. That's the anisotropy we introduced earlier.

If you have a vertical force on a tire, the pressure inside the tire resists that force by developing a contact patch of a size so that the internal pressure acting on the ground through the area of the contact patch equals the load on the tire.

The contact patch area (A) is equal to the vertical force (Fv) in pounds divided by the internal pressure (P) in pounds per square inch.

I'll include these equations which all express this same relationship. Starting with the last sentence in the previous paragraph:

$A\ (in^2) = Fv\ (lb) / P\ (lb/in^2)$

Multiplying both sides of the equation by P and rearranging you get:

$Fv\ (lb) = A\ (in^2) \times P\ (lb/in^2)$

Dividing each side by A and rearranging you get:

$P\ (lb/in^2) = Fv\ (lb) / A\ (in^2)$

Higher load on the tire at the same inflation pressure requires a contact patch of more area. The contact patch is roughly rectangular so the area is the length times the width. But the width of the tire is the width of the tread which is fixed by design, so to increase in area a contact patch has to get longer. More vertical load results in a longer contact patch. Lower internal pressure at the same load lengthens the contact patch. Of course the reverse is true and lighter loads or higher internal pressure generate a shorter contact patch.

As shown in Fig. 5.5 a longer contact patch means the tread cords bend through a larger angle coming into and going out of the contact patch. Flexing through the larger angle results in heat generation and higher fatigue stress in the cords. A highly loaded tire operating for some time at a low inflation pressure can generate enough heat and stress to cause a tire failure, perhaps a blow out. Internal pressure is the most important factor in the load-carrying capacity of a tire.

A Loading Example

Let's say we have a 4,800 lb car with equal weight distribution sitting on four tires. That's 1,200 lb of vertical load per tire. Each tire has an 8-inch wide tread and is inflated to 30 pounds per square inch (lb/in^2 or psi). To get the required contact patch area we use the first equation above and divide 1,200 lb by 30 psi getting 40 in^2.

We know the tread is 8 in wide, so dividing the contact patch area by that width gives us the contact patch length. 40 in^2 divided by 8 in gives us 5 in as the length of the contact patch of each tire on that car at that load and that inflation pressure.

If we add 1,200 lb to the car it weighs a total of 6,000 lb. Evenly distributed that's 300 lb more on each tire. Making the same calculation for length of contact patch gives us 1,500 lb divided by 30 psi divided by 8 in equals 6.25 in for a contact-patch length.

A lower inflation pressure requires a bigger contact patch to support the load. Here's a table to summarize load and inflation pressure effects for our example car.

Table 5-2: Load and Inflation Pressure Effects

Car Weight, lb	Tire Load, lb	Inflation Pressure, psi	CP Length, in
4,800	1,200	30	5.00
6,000	1,500	30	6.25
4,800	1,200	20	7.50
6,000	1,500	20	9.38

Overloading and Underinflation

A small increase in load or a small decrease in inflation pressure does little harm, but you can see in the table above that the contact patch length almost doubles with more load combined with a decrease in inflation pressure.

A good tire used normally is an amazing device. Absorbing the complicated cyclic stresses presents absolutely no problem for a fully-inflated tire used properly in the application environment for which it was designed.

But there are consequences attached to abusing a tire. Overloading and underinflation and high ambient temperatures combined with sustained high speed can cause tire failures. These failures might only create an inconvenience and a reason to use the spare tire. Or, as hundreds of Ford Explorer owners experienced, a tire failure can result in injury and death. A person driving a normal sedan which has a blowout can probably steer the car to a safe stop. A heavy, high-center-of-gravity Sports Utility Vehicle might not be stable at high speed after a blowout.

Low air pressure or increased tire load causes increased structural distortion. As the tire rolls this distortion pattern rotates around the tire, causing tread and sidewall components to increase in temperature. Add high road and air temperatures for an extended time and the tire temperature can exceed 300 degrees F.

Internal pressure can rise with temperature but a blowout due to internal pressure is unlikely. With extended time at high temperatures, however, the adhesives holding the tire together can lose strength and the tread rubber or reinforcing belts can separate from the body plies.

The point here is tires require adequate internal pressure, and only human attention can provide that requirement. Race teams check tire pressures almost minute to minute. Some racing organizations allow inflation pressure measurement devices that transmit tire pressure data to radio receivers in a team's pit equipment.

Drivers of road cars should look carefully at their tires daily and check inflation pressure with a gauge at least weekly. If you're not smart enough to check the pressure in your tires, you're not smart enough to drive on public roads. And make sure every tire has a good valve cap. Valves leak, so the cap on the Schrader valve is really the best and most positive pressure-retention device.

Braking and Acceleration Forces

When a vehicle accelerates, the engine creates a torque that gets to the tire through a driveshaft, transmission, differential, and half-shaft. The tire bead transmits forces from the wheel into the sidewalls and through to the tread, which grips the road and thrusts the vehicle forward. The forces in the sidewall change direction under braking. Since tire cords are much stronger in tension than in compression, at least two plies are needed in sidewall construction to accommodate these reversing forces. Fig. 5.6 illustrates the force reversal in sidewall plies. A proper inflation pressure creates enough static tension in the sidewall plies so that, under dynamic conditions, adequate tension is present at all times.

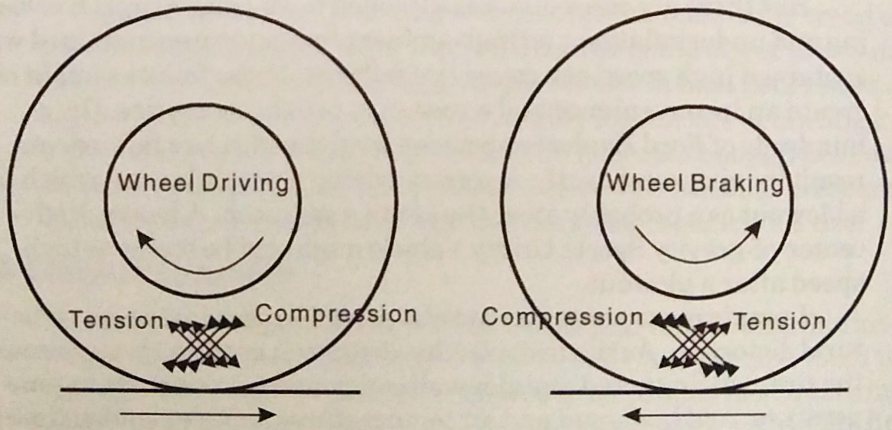

Fig. 5.6 Cord Forces in Sidewall Plies

Bias-Ply or Radial?

How do you design a tire? The vehicle and its operating environment is the starting point. The car probably has a specified wheel diameter and width. The car's wheel-well dimensions probably determine the outer diameter for the tire. Brake rotor diameter might dictate minimum wheel diameter. So really the tire designer doesn't have much choice when specifying the size of the tire. The vertical load on the tire and performance capabilities—mainly top speed—of the car determine the static loading and fatigue strength needed. The major design choices are what rubber compounds to use; what material to use in the carcass plies, belt plies, and belt caps; and the cord angles of various plies.

Cord angles in the carcass plies and tread belts are the most important choices a tire designer makes. Tire design evolution has produced three main types of tires: bias-ply, belted bias-ply, and radial ply. Thes are shown in Fig. 6.7.

In a bias tire for passenger car use there are usually two or four plies laid in alternating layers but all at the same angle with the tread centerline. A carcass ply laid parallel to the tread would be at zero degrees, while a ply laid perpendicular to the tread running straight from bead to bead is at 90 degrees. There are no extra tread plies in a bias-ply tire. Each ply is wrapped around the entire tire and bonded to both wire beads.

A bias tire has a circular cross section. In order to provide a flat tread, rubber has to be built up at the shoulders. Lateral forces on the tire during cornering can force the cross-sectional shape to deform, putting more force on the outside shoulder of the tread. This circular cross section limits the width of a practical bias-ply tire.

Belted-bias tires have a basic two- or four-ply body, with two or more additional belt plies between the tread rubber and the tire body. Cords in the belts are at smaller angles than in the body plies. The belt

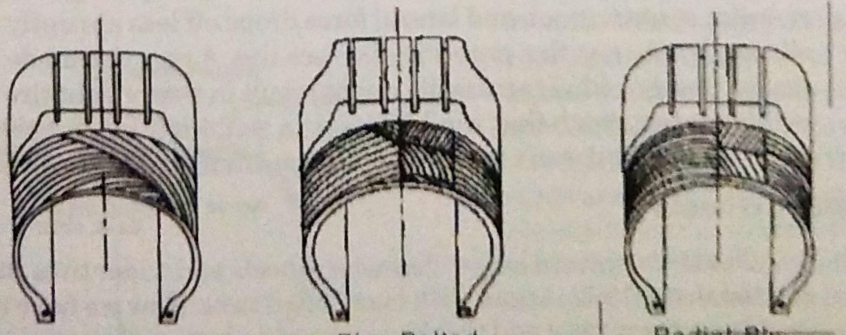

Fig. 5.7 Contruction Types

constrains both the width and circumference of the tread area, allowing a wider cross section and reducing tread movement in the contact patch. The belts also improve impact resistance in the tread area.

Radial tires are also belted but have carcass cords at 90 degrees to the tread centerline. Having plies running straight from bead to bead, radially when viewed from the side, results in an extremely flexible sidewall which acts independently of the belt, reducing tread movement in the footprint even more than in a belted-bias tire. Tires made with radial-cord construction produce less distortion in the contact patch and therefore less heat, less rolling resistance, and better wear. Tires for long-haul truck need to be very reliable and have low rolling resistance. Tires for this application have single-ply steel-cord carcasses.

Two other important tire design choices are the cross-sectional shape of the mold and the radius of the inflated, unloaded tread. We'll see the result of a mold profile change later in this chapter.

Street Tires vs. Race Tires

Passenger-car tires are relatively lightly stressed and can have carcass plies running from bead to bead at a 90-degree angle to the tire centerline. But few race tires are designed with purely radial plies. In race tires carcass plies need some cord angle for strength. As shown in Fig. 5.6, the sidewalls are in shear as they transmit braking and acceleration forces from the wheel rim and tire bead to the tread. The cords withstand stress much better in tension than in compression or bending, so it's necessary to have an angle other than 90 degrees. Since braking and driving forces work the sidewall in different directions, a tire needs at least two cord plies in the sidewall. That keeps at least one ply in tension under all loading conditions.

Race tires can be purely radial but generally have two-ply construction, with each ply at 85 to 70 degrees from the tread centerline but crossing each other. These angles might not be the same for both plies, giving an asymmetrical construction. Angled plies generate a rounder contact patch and lateral force drops off less abruptly at high slip angles than with a purely radial race tire. A race tire made with a single, purely-radial carcass ply might result in a very light tire with a stable contact patch that would tolerate a soft, high-hysteresis compound, but that doesn't mean that configuration would perform well.

Wider Wheels

The trend toward larger-diameter wheels and wider tires that started in the 1970s began with bias-belted tires. Now we have radials on all our street cars, and they're mounted on larger-diameter, wider wheels than in the 1960s. A radial tire with shorter, stiffer sidewalls generates less heat and can have a much softer compound and give the

same tread life. The result is a lower-pressure tire with a shorter, wider contact patch made from softer rubber. That gives us a longer-wearing, more responsive tire with a good ride and results in a safer, better-handling car.

Race tires have also gotten wider and the sidewalls shorter. This results in a more stable, more evenly loaded tread area that can handle higher lateral loads. A good thing too, as tread compounds have consistently improved, giving much higher levels of grip. More about race tires later.

Tire Construction

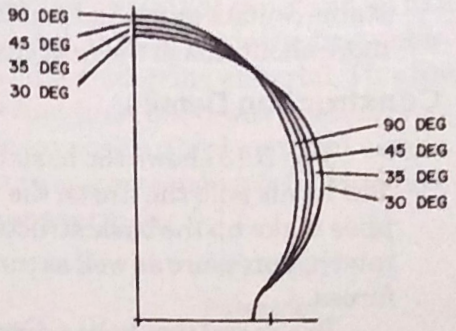

Fig. 5.8 Carcass Shape Varies with Cord Angle

A conventional bias-ply casing or carcass is built of two or more plies or layers—usually an even number and most commonly four—of parallel cords embedded in rubber. In the carcass the orientation of the cords in a ply lies at a specific angle to the centerline of the tire's tread. Half of the layers have a positive angle and half are negative. The angles are usually equal in magnitude and rarely exceed 38 degrees from centerline. As shown in Fig. 5.8, these ply angles determine the shape of the carcass.

Bias-ply tires have breakers, reinforcing layers in the tread area, that add to fatigue life. If the breakers are made of a stiffer cord or are layered at a very different, usually lower angle, the tire construction is called bias-belted. Manufacturers in the U.S. first made bias-belted tires in the 1970s as they geared up to match European companies making ever-more-popular radial tires. European car manufacturers began specifying radial tires because this design produced tires that were capable of the higher sustained speeds common on European highways.

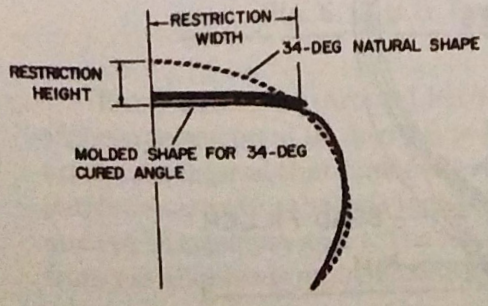

Fig. 5.9 Effect of Belt on Shape

In these newer tires the cords are placed at 90 degrees, perpendicular to the tread centerline. When viewed from the side, these cords are parallel to the radius of the tire, so

they are called radial tires, but are more correctly termed rigid breaker, radial-ply tires or belted, radial-ply tires.

The objective of a belt or breaker of low cord angle is to provide rigidity to the tread and generate a flatter contact patch, as shown in Fig. 5.9. The sidewalls usually contain only one pair of plies. The more flexible sidewalls and more rigid tread produce less distortion in the contact patch, and therefore less heat build up and longer life for the same tread compound. Actually tire companies use a softer tread compound in radial tires, getting more grip and better traction along with longer life. An added benefit, especially for race tires, is a more stable contact patch and smaller slip angles during cornering. We'll say more about this in the next chapter.

Construction Details

Fig. 5.10 shows the basic components of a belted or radial tire. The beads hold the tire on the wheel and anchor the plies. The tire plies make up the basic structure of the tire, resisting forces from internal pressure as well as cornering, braking, and accelerating forces.

In a radial tire, belts reinforce the tread area, restricting the outer diameter to a specific value. They also control the stiffness of the tread and determine the slip angle vs. lateral force characteristics of a tire design. Extra rubber components called fillers and inserts add strength or flexibility where needed in the sidewall and bead area.

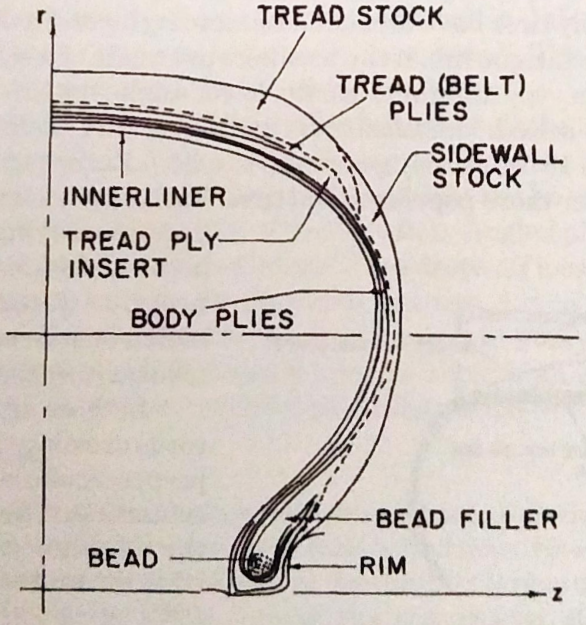

Fig. 5.10 Basic Tire Components

Not shown in Fig. 5.10 are extra components to prevent the belts separating from the carcass included in tires made for high-speed service. Fabric tapes added to the edges of the belts help. Some tires have a "cap" over the entire belt area that extends down into the sidewall. These caps can also be made of a continuous tape that is wound over the belts.

Reinforcing Cords

Tire cords are the source of the strength, flexibility, and fatigue resistance of a tire. They also give the tire shape, size stability, and shock resistance. There aren't many materials that can stand up to the stringent requirements of tire cord. J.B. Dunlop made the first pneumatic tire in 1888 with Irish flax as the reinforcing material. This fiber was one of the strongest known at that time, but it was gradually replaced by cotton, which was less expensive. Cord material usage during the middle of the 20th century is shown in Fig. 5.11. Modulus and tensile strength comparisons appear in Fig. 5.12.

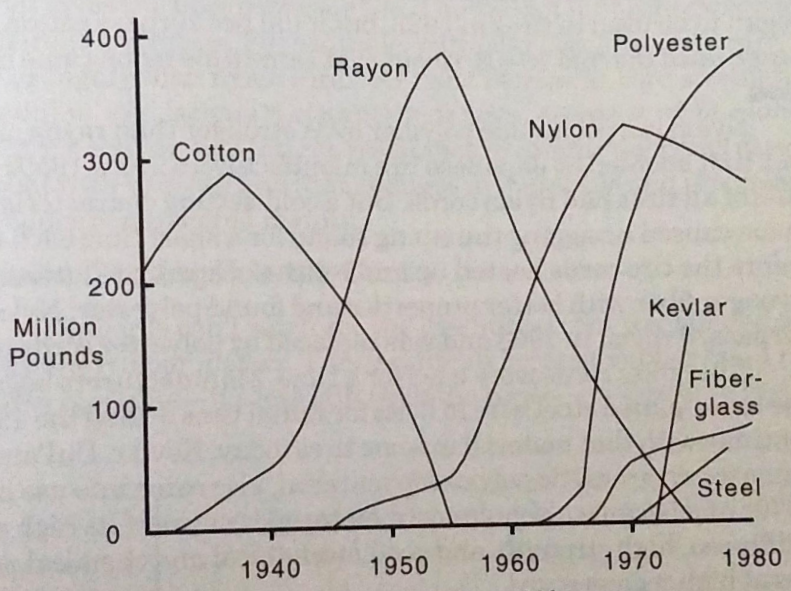

Fig. 5.11 U.S. Tire Cord Usage

Early tires made around 1910 used plain cotton fabrics composed of threads woven at 90 degrees to each other. Experience with woven materials showed that under the stress and deformation in the contact patch the crossing threads tended to saw back and forth on each other and cut themselves apart. The industry then began to use plies made from parallel cords embedded in a rubber matrix.

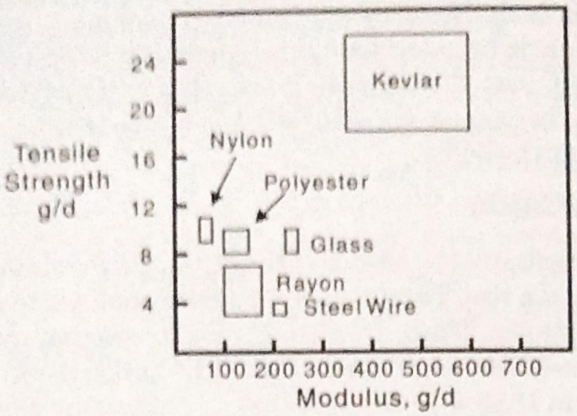

Fig. 5.12 Fiber Strength vs. Modulus

After World War II, increasing vehicle speeds and weights caused engineers to look for better cord materials. Rayon, a polymer made from wood pulp, has a higher tensile strength than cotton. Rayon began to be used in tires in 1923, but it did not surpass cotton in total usage until the mid 1940s. About that same time nylon came into use in tires.

Nylon is a polyamide polymer even stronger than rayon, and it was first adopted by Japanese tire manufacturers in the 1950s. By 1967 90% of all tires had nylon cords. But a cold-setting characteristic of nylon caused a nagging thumping sound for a short time each morning before the tire cords heated up and relaxed. Engineers looked for a stronger fiber with better properties and found polyester. Nylon surpassed rayon in 1963 and was replaced by polyester cords in 1974.

Fiberglass cords were used for a time. Manufacturers began to use brass-plated steel wire in belts for radial tires during the 1950s and continue with that material in some tires today. Kevlar, DuPont's brand name for an aromatic polyamide material, also came into use in the 1970s and became a popular cord material because of its high modulus (stiffness), high strength, and good mechanical and chemical properties at high temperature.

Polyester cord does not exhibit flat spotting and proved particularly suitable for bias-belted and radial tires. Goodyear started production of polyester tires for road cars in 1962. By 1969 polyester cords came close to equaling nylon in total usage. By 1975 50% of bias tires and 30% of radials made for passenger tires were made from polyester cords. Today polyester is used almost exclusively in passenger-car carcass plies.

Filament, Thread, Yarn, Cord

A cord starts out with a filament, which is a single fiber that is twisted into a thread. Humans first made textiles from plant and animal fibers such as cotton, hemp, and wool. Today a metal "spinneret" simultaneously extrudes several polymer fibers and spins them into a thread in one continuous operation.

Again, fatigue strength is the principal goal of every component of a tire. Twisting the fibers into threads starts to build a strong, fatigue-resistant material. Next the threads are twisted into a yarn. Finally several strands of yarn are twisted into a cord.

A thread twisted about other threads more times per inch is said to be more highly twisted than one twisted fewer times per inch. A thread can be twisted left-handed or right-handed. A yarn is usually made up of threads twisted in different directions to increase the fatigue strength. Cords are also made up of yarns twisted in different directions.

Tire and tire-cord manufacturers do not agree on which type of twist gives the best performance. They adopt different twists for different materials. For example, polyester cords are generally twisted more highly than nylon cords. As twist increases, cord strength, initial modulus, and fatigue resistance in tension decrease while elongation, rupture energy, and fatigue resistance in compression increase. As usual with tires we find that changes in materials and processes produce complicated results.

Adhesive Coatings on the Cords

The cords can't reinforce the tire unless they are bonded tightly with the rubber matrix. This is difficult because rubber has a much lower modulus—it's less stiff than the cords—as shown in Fig. 5.13.

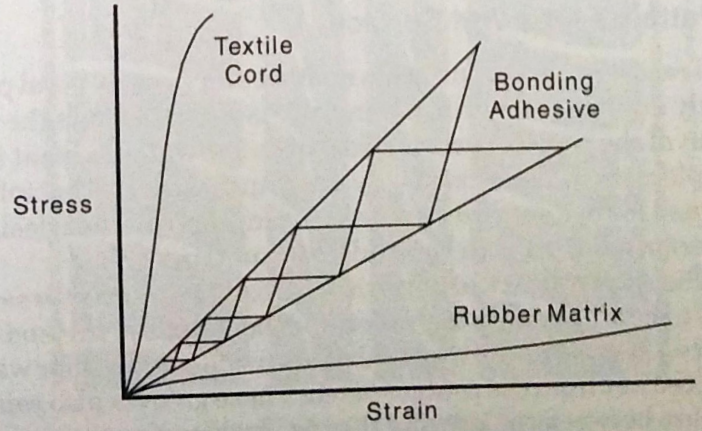

Fig. 5.13 Role of the Adhesive

The cords are coated with an adhesive to help the cord bond to the rubber during the curing process. When the finished tire is stressed the rubber will elongate much more easily than the stiffer cords.

It turns out that the adhesive between the rubber matrix and the reinforcing cords is very important in a race tire. When forces travel through the soft rubber to the relatively stiff cords they are buffered by the adhesive coating on the cords. One tire engineer told me it was similar to the way a thin rubber insole can help you stay on your feet all day. It seems the adhesive coating absorbs some shock and prevents the cords from tearing away from the rubber matrix.

Tread Design

The traction of a tire on a dry surface is diminished by any tread pattern. Slicks—treadless tires as seen on racecars—generate the best dry grip because of the uninterrupted support of lateral and longitudinal shear forces produced by the road during cornering, braking, and acceleration. Any tread pattern creates voids in the rubber surface, leaving areas of rubber unsupported in shear and lowering the area in contact with the road. Tread patterns also produce local areas of high load at tread edges due to bending of freestanding blocks of rubber.

Tires produce more grip when there is more tread area in contact with the road. This is due to both adhesion and mechanical keying of the rubber to the road.

The previous paragraphs appear to be straightforwardly obvious, but only a few decades ago race-tire engineers believed tread pattern designs helped cool tires and contributed to traction. Even after track testing showed that a smooth tread of continuous rubber produced more grip than a treaded tire, the transition to slicks took some time. An interview with Mario Andretti in a later chapter provides an interesting insight into the development of racing slicks.

Tread Patterns for a Wet Surface

Traction on a wet surface is another story, and a tread pattern greatly improves wet grip. When a tire is moving so fast the water can't get out of the way the tire can ride up on the water in what is called aquaplaning, a condition of very low grip and loss of control. Tires designed for use on road cars need a compromise tread design providing performance in both wet and dry conditions.

The role of the tread pattern on a road tire or a wet-weather race tire is to help eliminate the water from between the tire and the road surface. Grooves in the tread rubber provide channels for water squeezed out from the contact patch. These grooves also raise the pressure between the tire and the road by lowering the area of con-

tact. High loads at tread edges that will overheat or abrade in the dry are cooled and lubricated in wet conditions. These edges help squeeze water from the rubber/road interface.

As usual there are trade-offs. A more narrow tire allows water to flow out more easily. The water simply has less distance to travel. More circumferential tread ribs are better than less. There is an optimum rib width, and you can see that width on almost every rain tire. Tread ribs at angles of more than 50 degrees to the tire circumference are better than ribs at smaller angles. Those trade-offs seem to describe the tread pattern we've all seen, the familiar "Gatorback" rain tire.

As a tire wears, tread grooves become more shallow and they can't move the volume of water as well as when the tire was new. A Bridgestone/Firestone tire brochure shows a sipe, a narrow slit in the tread rubber, that has a key-hole shape in cross-section. When the tire wears down to the change in cross-section, the sipe becomes wider and the tread pattern more open. Wet grip increases because of higher unit-area loading and better water-handling. This feature creates manufacturing difficulties because of the bulge at the end of the mold feature that has to be pulled through the narrow sipe cross-section as the tire comes out of the mold tooling.

Tire Noise

For road tires noise is an issue. Everyday drivers want their tires to wear forever and require no attention. They certainly don't want tire noise to interfere with listening to their favorite CD. Fig. 5-14 shows five different-sized tread blocks as used in a Bridgestone/Firestone tread pattern.

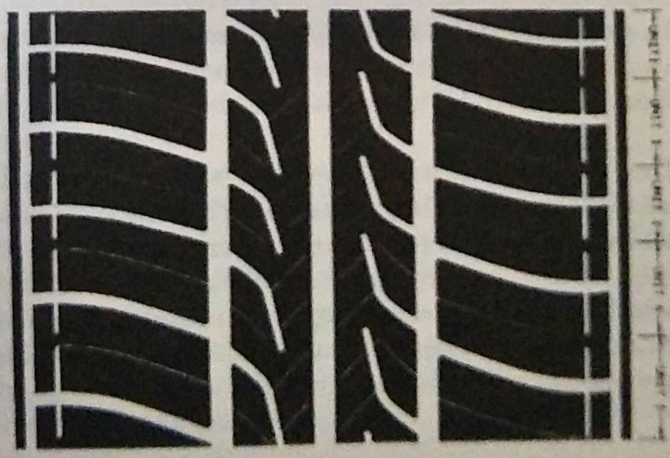

Fig. 5.14 Noise Reduction, Five Different-Size Tread Blocks

If all the blocks are the same size the noise produced by their interaction with the road has a single tone. Varying block sizes produce a range of tones called white noise which doesn't sound as loud to humans. The sound level is the same, but the noise is not so bothersome.

Special Case: Sports-Utility Vehicles

Sports Utility Vehicles seem to be an exception when it comes to tires. People don't mind noisy tires on those cars. The knobby, wide-open treads on SUV tires are there for a reason—less grip. SUVs have a narrow track and a high center of gravity so they tip over easily. A tire with normal grip could pose a safety hazard. SUV tires are actually designed for low grip to avoid rollovers. What about braking traction? It looks to me like that has to be less also.

For me better tires are those that generate more grip in all conditions. If your vehicle is so big and unwieldy that better tires are a hazard, maybe that type of vehicle is a poor choice!

Manufacturing Process

Fig. 5.15 comes from *The Science and Technology of Rubber* edited by Frederick Eirech and summarizes the tire manufacturing process. A fiber is spun into thread, the thread into yarn, the yarn into cord, and the cord is woven into fabric and coated with an adhesive. A mixture of rubbers and additives undergo mechanical and thermal processing in machines called Banburys and mills, resulting in specific rubber formulations called compounds that are used in different parts of the tire. Bead wire is coated and wound. To ensure quality control, incoming materials are inspected against required specifications. After each critical process, portions of the combined materials are also inspected.

The cord fabric and body-ply rubber come together in a calendering machine. Fig. 5.16 shows a calendering machine at Hoosier Tire near South Bend, Ind. This machine is about 30 feet tall and 150 feet long.

The cord material has a few thin cross threads to hold and space the individual cords during processing. This fabric, pretreated with an adhesive coating, is offered to the calendering machine as a 4-foot diameter, 60-inch wide roll weighing about 2,500 pounds. The machine feeds the fabric through a holding trough filled with rubber, and then rollers, called "calenders," press the resulting cord-reinforced rubber sheet to a specified thickness.

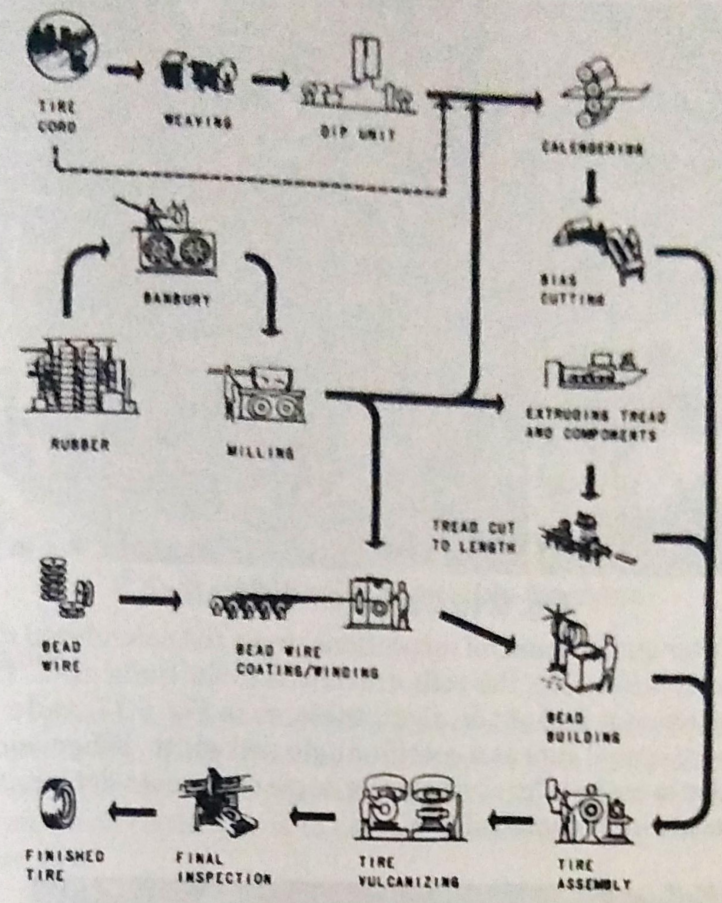

Fig. 5.15 Tire Manufacturing Process

Although it sounds simple, this machine is complicated. Computer control ensures product consistency. Both the fabric and the rubber have to be heated before they come together. The spacing of the cords is critical. The rubber has to completely surround the cords, but the cords can't be too far apart.

The tension on this long web of material is closely monitored and controlled. Lateral position of the fabric web is critical also. Once the machine is running, stopping it would create costly dead time and waste product. New rolls of cord are spliced in "on the fly." At the end of the process cooling drums remove heat from the material before it's stored on take-up rolls. The result is huge rolls of body-ply material with the layers separated by polypropylene film treated to prevent them from sticking together.

Fig. 5.16 Calendering Machine

After quality-control inspections prove the calendered material is within specification, the rolls are moved to the build area. The cord/rubber sheet is laid out on a long table, as in Fig. 5.17, and a worker makes diagonal cuts at a specific angle and width. When laid on a cylinder to make a "green tire" the angle of the cuts determines the cord angle in the finished tire.

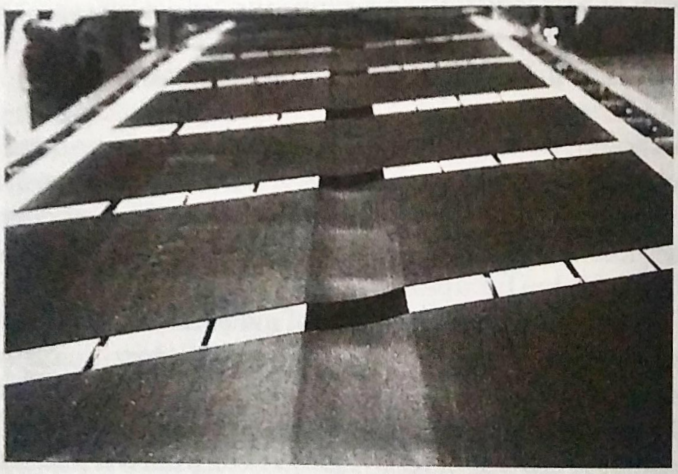

Fig. 5.17 Layout Table

Tread Material

Tread compound, a different mixture from the rubber compound used to produce body plies in the calendering machine, is extruded using a die with an elongated rectangular shape. It produces a sheet of

rubber that is laid onto the layers of body plies. Tire manufacturers are beginning to extrude tread that is made up of two different rubber compounds. Tread wear exposes a compound with more hysteresis, maintaining wet traction even though the tread pattern has lost its full depth.

Fig. 5.18 Bias-Ply Assembly Machine

Assembly

A green (uncured) bias tire is assembled on a machine similar to the one in Fig. 5.18. Green tires are stored for a short time before the curing process. At this point the bead wire and white rubber inserts in the sidewall (if the tire is to be a whitewall) come together with the green tire.

A part of the final assembly machine folds some of the sidewall over the bead wires, so they are captured and bonded into the structure. Then heat and pressure form and cure the tire inside a mold that also determines the tread pattern.

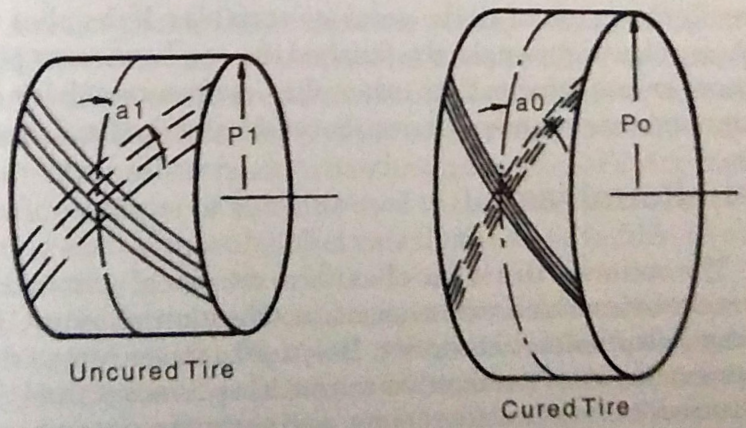

Fig. 5.19 Bias-Ply Cord Angles before and after Curing

During this process a bias-ply tire is expanded from a cylinder to a torus. The cord angles, determined by the diagonal cut of the ply material, changes to the cord angle in the final assembly. This angle change, shown in Fig. 5.19, is called pantagraphing.

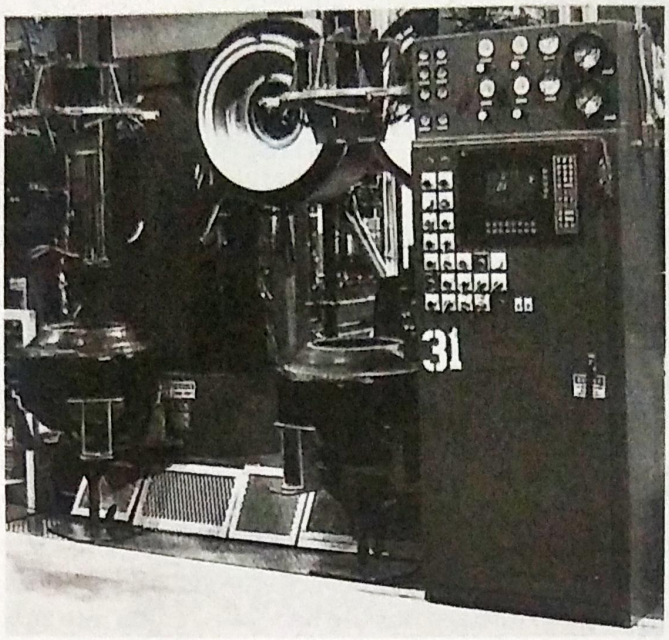

Fig. 5.20 Radial-Ply Assembly Machine

A radial tire is assembled on a machine as shown in Fig. 5.20. The assembly is expanded before the belts and tread are applied, so the cord angles don't change during curing. Some manufacturers apply the tread by winding a rubber tape onto the carcass before molding. Most use an extruded band of tread rubber.

The curing process is extremely critical, but the finished product is really the result of all the previous variables. If the plies were not laid up at the right angle, the finished tire can have some plies that are in more or less tension than other plies. An incorrect body rubber compound can be under- or over-cured during the final process.

Tire Nonuniformities

The optimum tire is one of uniform rotational symmetry having no characteristics which will cause noise, vibration, shimmy, or any other perceptible problems in service. But, due to the nature of their construction, tires have anomalies caused by splices, belt misplacement, uneven cords, bead misplacement, and variations in cord angle and cord count, as well as other variable conditions. A finished tire is a

molded, bonded system that is difficult to inspect without destroying the part. Automation in tire manufacturing and methods of nondestructive testing are keys to making good tires. Almost all heavy truck tires, tires made for aircraft, and race tires are 100% X-rayed after molding.

But defects can be found in a very small number of tires. Quality control is high and few defective tires get as far as the highway. Dimensional defects include out-of-round variations in the outer diameter called radial runout and a similar sidewall condition called lateral runout. Both defects can cause harmonic vibrations.

Force variations are another possible defect. A radial force variation can be caused by radial runout. Variation in stiffness around the tire or varying mass distribution can cause harmonic disturbances that increase slightly with speed. Most tires have some mass unbalance, but the wheel/tire assembly can be balanced by attaching weights to the wheel.

Lateral force variations are another type of defect. Conicity, where one sidewall is longer or stiffer than the other, generates a force toward the apex of the cone. This is also called pseudo-camber and can be built into a race tire to simulate camber thrust on fixed-axle suspensions. If a tire is built with ply-angle variations, that tire can generate lateral force at zero slip angle. This is also called ply steer, and it reverses with tire rotational direction.

Conicity can be a manufacturing problem due to misplacement of the belts or some other mistake. Ply steer is a design problem and rotating the tire inside out on the rim does not change the direction of the side force. A tire that shows conicity without ply steer will show a constant lateral force at zero slip angle. Turning the tire inside out on the rim will change the direction of the side force.

The Hazards of Batch Processing

A major goal in the manufacture of any product is uniformity. You'd like every unit to be identical to every other unit except for planned changes that result in better performance or decreased manufacturing costs. Many of the components that make up a finished tire are themselves made in batches, quantities of a size that fit a specific container or machine used in the manufacturing process. Making each of those batches exactly the same is difficult and deviations occur.

Continuous manufacturing operations are inherently easier to monitor and control. Electrical wire and cable manufacturing and petroleum-product refining are examples of continuous production. If the same raw materials flow into the same process stream, good process control can yield consistent product.

In batch manufacturing, measurements of raw materials can vary from batch to batch due to operator error, machine malfunction, or measuring tolerances. Maybe the deviation matters and maybe it doesn't.

Raw-material manufacturers can make changes in the specification of a product and usually test the material to make sure customers will not be adversely affected. But maybe that change causes an unobvious difference in a finished tire.

Let's say it again. A tire is a complicated, extremely useful product used in a critical, safety-sensitive application by most of the people on this planet. Rubber is necessarily processed in batches. Tires are made one at a time in molds. Although automation of tire manufacturing continues to expand, most tires, including race tires, are made by a process that includes batches of materials and human operators performing craft-sensitive tasks.

So, in spite of intense attempts at quality assurance by tire manufacturers, every tire is somewhat different from all its siblings. Sometimes the difference makes a performance difference and sometimes it doesn't. Considering the manufacturing complexity and hard use a tire sees in service, relatively few problems occur. I wish my computer hardware and software were that reliable.

Manufacturing Developments

The tire industry would like to simplify tire design and manufacturing to achieve even better qualify control along with lower costs. Cordless tires, tires cast in molds, have been made and tested, but no product is yet available.

Small changes in the shape of the mold used in final curing can have significant effects on the performance characteristics of the finished tire. Fig. 5.21 shows a small change in the shape of a mold cavity. The dotted line on the left is the vertical centerline of the mold. With the change in the mold, the uninflated shape of the sidewall plies is more flat, as shown by the dotted line. If these plies start out more flat, they distort to a higher tension when inflated, and in use, the tire will have a more stable contact patch and generate less noise.

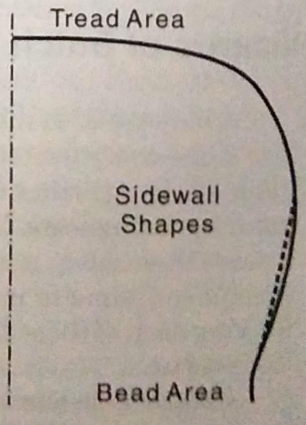

Fig. 5.21 Mold Cavity Shapes

Another way to achieve a similar result is to make the mold so the width from bead to bead is larger than when the tire is mounted. After mounting the beads are closer together, adding tension to the sidewalls.

The Tire Industry Isn't Healthy

Automated, more flexible manufacturing would be a boon to the tire industry. Current processes and equipment require large amounts of hand labor and in-process inventory. The industry is still recovering from the introduction of the radial tire, which has twice the service life of bias-ply tires, resulting in excess manufacturing capacity. Poor marketing and trade-secret paranoia have prevented consumer education. The tire companies find it difficult to differentiate their products from those of other tire manufacturers. As a result, tires are considered a low-value commodity by consumers, who often end up using price as the sole purchasing criteria. A poor product image and intense competition among manufacturers depresses profits. Capital for R&D or new manufacturing equipment is scarce.

Automated Manufacturing

A possible future for tire manufacturing might be MIRS, standing for "Modular Integrated Robot System." Reports of this new production system for tires introduced by Italy's Pirelli have appeared in various publications during 2001 and 2002. Other automated production systems exist, notably Michelin's C3M system, Bridgestone's Tochigi, and Goodyear's IMPACT, but Pirelli is talking about widespread implementation, including placing MIRS systems close to or inside of auto assembly facilities to provide multi-product, just-in-time tire production.

MIRS is different in that, unlike traditional labor-intensive tire factories, MIRS tires are produced entirely by machine. A series of software-controlled robots process tires right through construction to molding and vulcanization. Tires of different sizes and even different designs can be run efficiently in small batches.

The MIRS system is small and modular. The basic production line fits in a mere 3,500 square feet and costs a modest $45-50 million. Working continuously seven days a week, this mini-factory can produce a million tires a year at an overall cost 75% of that of a traditional, mid-size plant, which might produce 6 million tires a year.

MIRS can be installed almost anywhere, and production expansion is accomplished by installing additional modules alongside the existing ones. Furthermore, a MIRS plant can be assembled quickly wherever it is needed. This is in huge contrast to the traditional, capital-intensive tire plant.

MIRS systems could help elevate tires from the black, smelly, commodity product of today to a sophisticated element of a vehicle's overall design. For instance, the MIRS system makes it easier to embed in the tires intelligent sensors that are linked to a car's electronic information system and continuously monitor critical tire parameters such as internal pressure, temperature, and tread thickness. These systems could trigger alarms if they sense a low tire pressure or a dangerous event such as a puncture. Optical sensors could monitor wear to determine a service point. Such improvements could have a big impact on any large fleet of vehicles but especially on cross-country trucks, which make money by spending as little time as possible off the road.

"There is no such thing as a free lunch."
—Anonymous.

CHAPTER 6

TIRE BEHAVIOR

After chapters on rubber, friction, and tire design and manufacture, here's what we know so far:

A tire, one of the most useful and complicated devices made, is a gas-pressurized, textile/rubber composite with a rubber traction coating. Rubber is a mixture of polymers, reinforcing fillers, and other chemicals that, after vulcanization, have viscoelastic characteristics that are not fully understood. Tires are difficult to manufacture consistently, but current technology and manufacturing facilities produce an extremely reliable, durable, and inexpensive product. A finished tire is a bonded unit, so failed tires are difficult to analyze post-failure. Rubber friction, mainly due to adhesion and deformation, exhibits viscoelastic effects and is sensitive to compounding variations, vertical loading, sliding speed, and temperature.

Now let's look at some of the details of how tires behave during use.

How a Car Turns a Corner: Revisited

We introduced these concepts in the first chapter and will go into more detail now.

At any moment in time a car turning a corner is accelerating toward the center of an instantaneous circular arc as in Fig. 6.1. The radius of that arc might be changing, but at any instant the path is a specific arc. The car's tires supply the force to turn the car. That force is called lateral force or side force or just grip. In this schematic we combine the lateral forces of the four tires and have it acting on the center of gravity (CG) of the car.

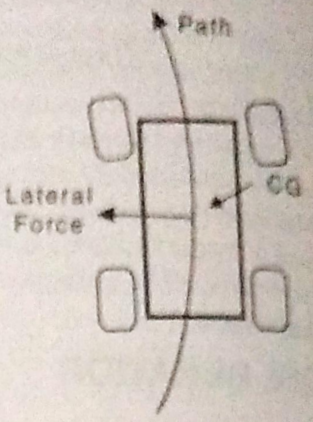

Fig. 6.1 Car on a Circular Path

Slip Angle

A tire produces lateral force with a slip angle, shown in Fig. 6.2. Slip angle happens when the steering wheel is turned from straight ahead and it's the angle, "a" in the schematic, between where the tire is pointed and where the car is actually going.

The elastic nature of a tire makes a slip angle possible. The tire grips the road but also yields to external force, resists movement with an opposing force, and recovers when the external force is removed. This elastic characteristic of a tire allows the tire to be pointed in a direction different from the direction the car is headed.

It's important that we understand what's going on in the contact patch between road and tire that creates a slip angle. The tire is rolling, so any one point on the tread rotates into and out of the contact patch with every revolution. When the tire is rolling in a straight line that point on the tread sees a regularly repeating thump of vertical force as it rotates into the contact patch and momentarily bears this tire's share of the vehicle weight.

As soon as the driver turns the steering wheel, conditions change at the contact patch. Steering input causes the tire to turn, and now the leading edge of the tread rotates on to the road slightly to one side of the rest of the contact patch. As the tire rolls, each small increment of tread rubber coming onto the road sits down another small distance toward the direction the tire is pointed.

As the car's weight comes onto these small increments, they stick to the road. The tread is now pulling the rest of the tire and generating forces that go through the wheel and the suspension to turn the car. The force needed to change the car's path is generated by the tire. This is called lateral force or side force.

As in Chapter 1, we can use the analogy shown in Fig. 6.3 of a person walking to further explain slip angle. A person walking on a circular path changes direction in small increments. At each step a foot is turned in a small angle toward the path of the arc. The heel contacts the ground and the rest of the shoe comes down in this new direction. As weight comes onto the shoe sole, the shoe is pointed in the new direction. The next step also changes the walker's path a small amount. These small changes continue to build up and the direction the walker is headed changes also.

That's exactly what happens when a tire is given some steering input. Each small increment of tread rubber rotating into contact with the road surface latches onto the road surface a small increment toward a new heading. As long as the steering input remains the same, each increment of the tread contacts the road the same amount toward the new direction. The rest of the contact patch thinks it's headed in the old direction, but the old contact patch continually rotates out of road contact. The next time that part of the tire touches down, the heading of the tire and car will have changed.

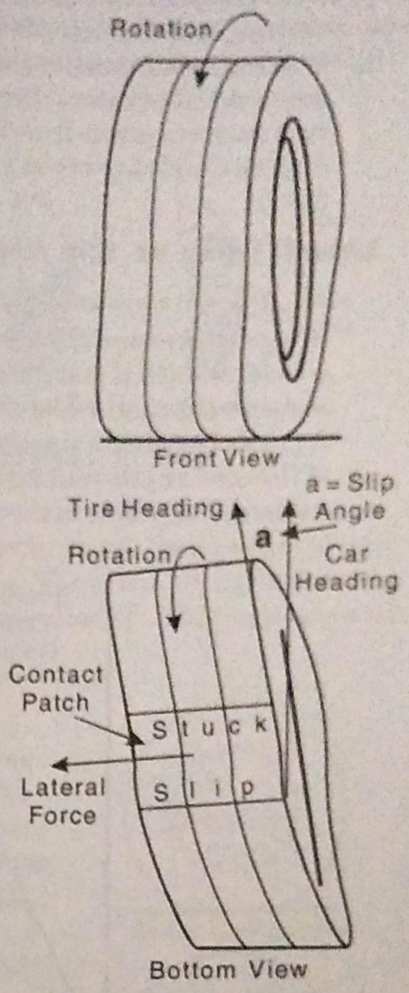

Fig. 6.2 Slip Angle

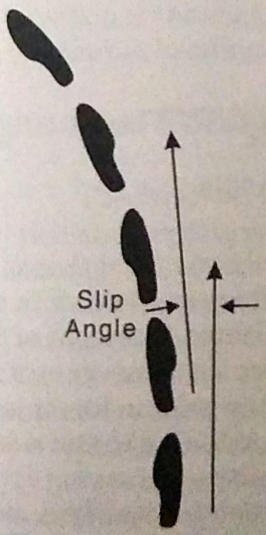

Fig. 6.3 Footstep Analogy for Slip Angle

The tire tread actually deforms as it rotates through the contact patch area and then recovers as the car's weight comes off the contact patch. The force needed to deform the tire is what produces the lateral force needed to change the path of the car.

When the front tires respond to steering input with a slip angle and begin to develop lateral forces, the front of the car turns to a new heading and the entire car rotates in yaw. If the rear wheels were mounted like casters they would swivel and the rear of the car would spin outward, away from the turn. But the rear tires are fixed in direction and they resist yawing with their own slip angles and lateral forces.

Lateral Force vs. Slip Angle

Fig. 6.4 shows the general relationship between the lateral force a tire generates and the slip angle of the tire. A tire does not generate side force until it is steered away from its current course and it assumes a slip angle. The shape of this curve is not the same for all tires. A graph like this is a specific characteristic of a tire design—the result of the cord angles and rubbers used in the tire structure and the rubber compounds in the tire tread.

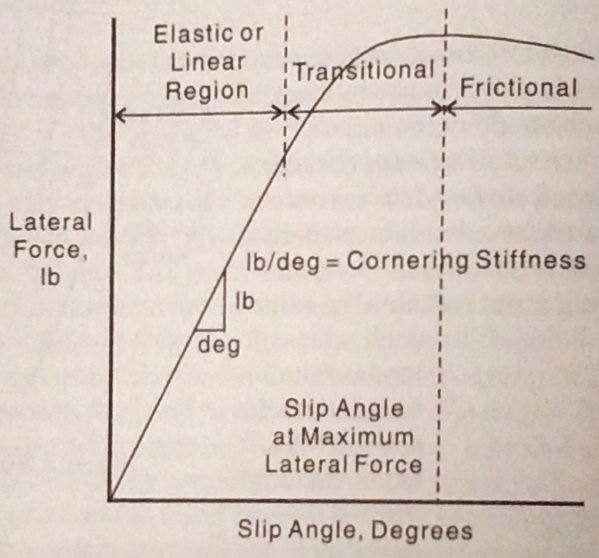

Fig. 6.4 Side Force vs. Slip Angle

Notice that this curve has three distinct shapes. First there's an almost straight section at small slip angles where an increase in slip angle gives a proportional increase in lateral force. The slope of this section of the curve is the "stiffness" of the tire. In this region of the curve the tread is not sliding on the road at any point in its contact patch. A tire designed to have more stiffness in the tread and sidewalls will have a steeper slope in this area of the curve.

At higher slip angles portions of the tire patch are sliding, and you get less increase in lateral force with an increase of slip angle. This is called the transition region. As the curve tops out, more of the contact

patch is sliding and the tire produces less lateral force. After the peak of the curve, lateral force can fall off 30% within a few degrees of extra slip angle. At these high slip angles most of the contact patch is sliding, producing a lot of heat and wear.

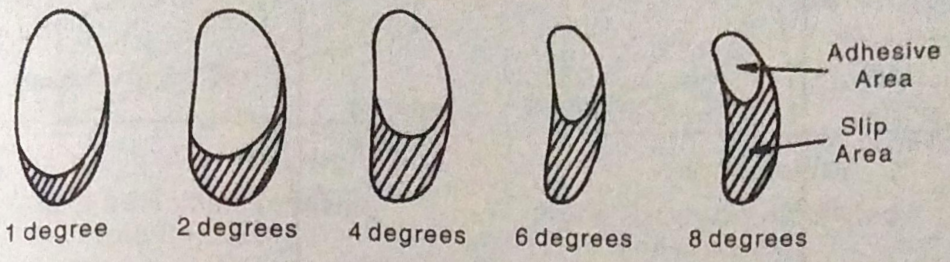

Fig. 6.5 Contact Patch Areas of Slip and Adhesion

The schematics in Fig. 6.5 came from visual observation of contact patch shapes at varying slip angles. The tire is rolling in the direction of the top of the page and is turning left. This contact patch is much more narrow than that of a current tire, but that helps us see the changes more easily. Notice how the leading edge of the contact patch curves toward the turn. This is the result of slip angle; the tire is pointed in the direction forced by steering input. The leading edge of the contact patch is pointing in the steering direction while the rearward portion of the contact patch lags behind on the old heading.

Longitudinal Forces

The forces on a tire during acceleration and braking deform the sidewall enough that the contact patch moves a noticeable amount. The three schematics in Fig. 6.6 show how braking and driving forces can move the contact patch compared to static conditions.

During braking and acceleration tires generate longitudinal force, and there is some longitudinal slip between the tread and the road. This shows up as a difference between the actual rotation of the

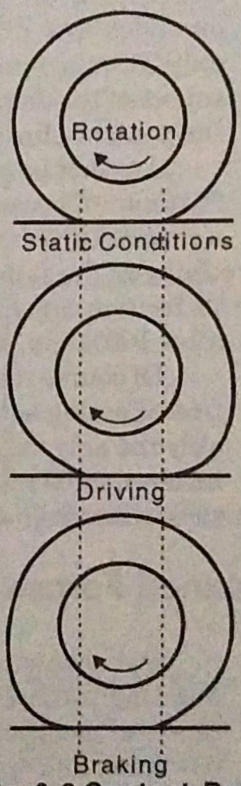

Fig. 6.6 Contact-Patch Migration

tire and the rotation needed if there were no slip. Under hard acceleration the tire turns a little faster, and during hard braking the tire rotates less than it would if there were no slip. These two graphs show driving (Fig. 6.7) and braking forces (Fig. 6.8) vs. percent slip.

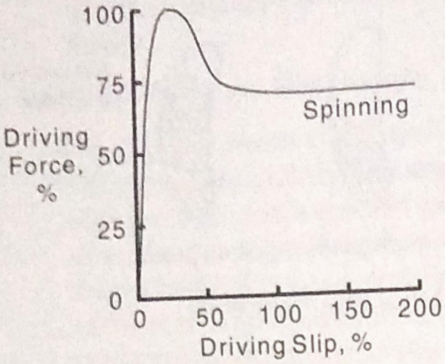

Fig. 6.7 Typical Driving Force vs. Slip

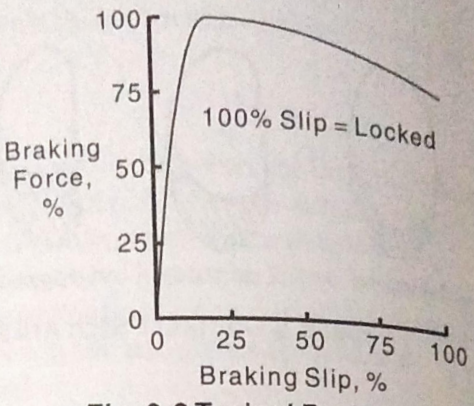

Fig. 6.8 Typical Braking Force vs. Slip

The shape of these two curves suggest the tire reacts to braking and driving forces in different ways. As soon as driving slip approaches 50%, driving force falls off rapidly. Braking slip falls off at only 25% slip, but the force reduction is more gradual. I don't know the source of the data for these graphs but they might look more alike if the percent-slip scale were the same.

Another possibility is that the driving-force curve drops off and flattens out because the tire is still spinning and the tread surface has a chance to cool, where the braking tire is locked at 100% slip and slides on the same contact patch. This heats up the rubber, lowering its friction capability. I'll bet the braking curve continues to fall off after 100% slip, off the scale of this graph.

Of course these curves represent generic data from passenger-car tires. Testing at high slip is difficult due to the forces involved. Probably the only valid test vehicle for racetires is a competitive, fully-instrumented racecar driven by a world-class driver. Even then the tire/road/driver system varies continuously creating noise in the data.

Combined Forces

Data showing tire behavior under a combination of both lateral and longitudinal slip is almost nonexistent outside of the tire companies' test facilities. Graphs similar to Fig. 6.9 and 6.10 appear in various books and are very general. The main point made is that lateral force falls off rapidly with any additional slip due to acceleration or braking.

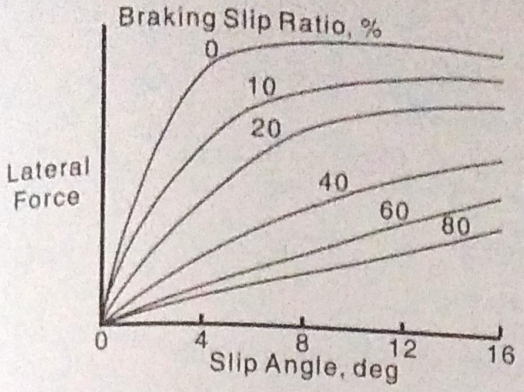

Fig. 6.9 Combined Braking and Cornering

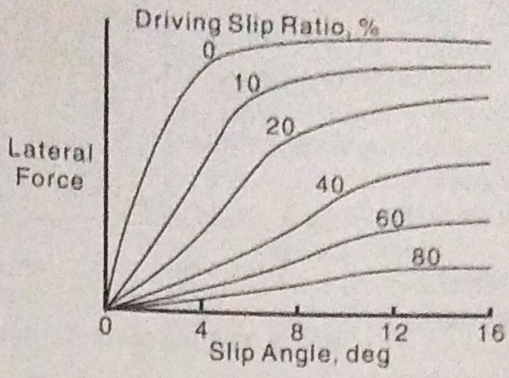

Fig. 6.10 Combined Driving and Cornering

Friction Circle

The graphs above show that tires produce maximum lateral force when there are no driving or braking forces. The friction circle graphic in Fig. 6.11, actually a half-circle because the other half would look roughly the same, illustrates how lateral force falls off in the presence of braking or acceleration. The concept is equally applicable to a single tire or a vehicle.

The three thick arrows show maximum driving, braking, and lateral forces when those are the only forces present. When the tire sees a combination of forces, driving force and lateral force are shown here, maximum lateral force is not available. In this example, adding driving power to the tire reduces the available lateral force. Of course this is what we feel powering out of a slow corner—power oversteer—one of the most fun things you can do with a car.

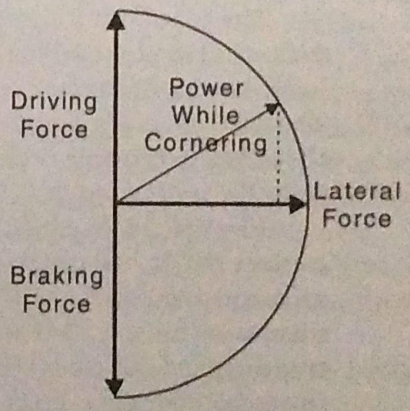

Fig. 6.11 Friction Circle

Lateral Deformation of the Tread

It bears repeating that it is the elastic characteristic of the pneumatic tire that allows the generation of a slip angle, and it is the forces resisting the deformation of the tire structure combined with the tread's grip on the road that allows a car to turn a corner at speed. The schematic in Fig. 6.12 represents tread deformation in the contact patch of a tire rolling to the left with some right-hand steering angle

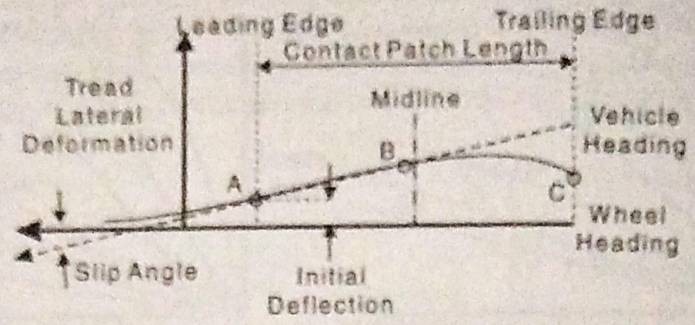

Fig. 6.12 Lateral Deformation in the Contact Patch

and a resulting slip angle. The dotted line with an arrowhead represents the direction the vehicle is headed. The angle between the vehicle heading and the wheel heading is the slip angle.

The curved solid line represents tire lateral deformation from its unstressed position. Once again, it is the tire's resistance to this deflection that creates the lateral force that turns the car. The curved line tracks the lateral deformation of a single point on the surface of the tread rubber as it travels through the contact patch and is deformed by the road acting on the tire. The solid line with a left-pointing arrow is the zero-deflection line. The difference between those two lines is the distance the tire deflects.

The tread rotates into the contact patch at point A, and the lateral deflection at point A is called the initial deflection. Point A marks the leading edge of the contact patch, but deflection starts prior to that. The tire carcass has some stiffness and the tread is even more stiff, so there has to be some deflection starting well before the tire rotates into the contact patch.

From point A to point B, somewhere near the midline of the contact patch, the tread stays stuck to the road (at this slip angle anyway) and lateral deflection in the carcass and in the tread rubber increases linearly. But at some point the force required to deflect the tread exceeds the local friction coefficient times the local load, and the tread begins to slide on the road. At higher slip angles sliding starts farther forward, as we saw in the drawings in Fig. 6.5. More about this shortly.

At point B the tread begins to recover from maximum lateral deflection and at point C the tread rotates out of the contact patch. Notice that there is still some lateral deflection at C. The tire has to rotate farther before the lateral deflection fully recovers. Once again it is the remarkably strong but elastic nature of a tire that enables it to deform, assume a slip angle, and generate turning forces.

Wide Tires Are Better

In June 2001 I learned that Jim Hall's Chaparrals would be featured at the vintage races at Road America near Elkhart Lake, Wis. As a bonus the event title was The Brian Redman International Challenge, and Brian is a subscriber to my newsletter. Jim Hall, grand marshal of the event, was one of the first technically educated people involved in designing modern racecars, and I wanted to talk to him about his experiences. I called the track and requested an interview with both guys. Everyone showed up on time at the media center. One of the first subjects we talked about was tires.

Paul: "Back in the '60s you had some good battles in your little Porsche with Delmo Johnson [Jaguar D type with a Chevy V-8 engine] at Green Valley Raceway near Dallas."

Jim: "Yeah, that was a big car vs. a small car, and that was good. I enjoyed those races. That was the real reason I got the Porsche and it was a great experience for me because it was a different-handling car and it was a car that had a lot of racing history and I got to experience that. The Porsche RSK was a helluva car. It would take a set real nice and you could drive it around a corner with the throttle and it seemed like it had a lot of cornering power.

"We used to wonder, before we began to think of the science of it, why the little cars like the Porsches would beat the big cars. We'd go to the short tracks and they'd be all over us. They'd come off the corners a little quicker, they'd squirt for a little while, and they'd go deeper into the corners on braking. I'd wonder why I was having so much trouble staying ahead of this guy in this little 1600 cc car. What it was was he had about the same size tires as I did but the car was a lot lighter. He got a lot more cornering power than I did. That wasn't so obvious to everybody in those days, how important the tires are."

Paul: "We know now how important tires are. For both of you, Jim and Brian, has there been some time when tire development jumped ahead and you went seconds faster?"

Brian: "I was driving a Lola T70 Can-Am car in England in 1966. We were running on Dunlop Green Spots, I think."

Jim: "Only about five and a half inches of tread on those, I think."

Brian: "Bruce McLaren was the official tester for Firestone tires. They brought three of their cars to Oulten Park in North England, which was only an hour from where our cars were garaged. The McLarens all blew up and the Firestone people asked us if we could bring our car to fill in the next day. We did. Firestone had a wider tire that was almost a slick and we went four seconds faster than our previous best."

Jim: "That tire had almost no tread, only some little sipes cut in it."

Brian: "Even then the wider, slick tires didn't get going for several more years."

Jim: "During that time I was with Firestone. Bruce and I were the guys that ran Firestone tires. I did the testing in the States and he did it in England. When we first built the so-called automatic car it was a single-speed torque converter, with no transmission. All you did was put it in gear and go. It had a two-to-one torque multiplication out of the torque converter so it was like having a high second gear. On the Dunlop Green Spots, the best tire we could get, we could spin the tires from about 10 feet out of the gate up to 80 mph or something. So we thought, 'Why do we need any more transmission than this?' It was fine not having any gears.

"Then I got with Firestone and they brought us development tires. The first tires we got were wider than the Dunlops. They had an inch or so more tread on the ground. We were runnin' 7-inch rims in the back I think, or maybe 6-inch in the front and 8-inch in the rear. Or 5s and 7s. I don't recall exactly. They were 15-inch diameter wheels. We put the Firestones on and tried them in our skid-pad testing.

"We had started runnin' skidpad tests, just going round and round on the skidpad. We did a lot of tire testing and that's the way they checked the friction coefficient to see what kind of cornering power you're actually getting. We got good at it and we found out we could balance the car this way. You could put the car on the scales and balance the weights but you go out there on the skidpad and it won't turn the same both directions because somethin' is amiss in the car.

"It was a little bit more technical than we could figure out. Either the chassis was tweaked a little bit or the caster was off on one side or somethin' and you'd find out running around on the skidpad that, in one direction, it would go up to 0.98 Gs and only 0.92 the other way.

"That skidpad was really handy. We'd crank a little weight in the car to balance it. You could look at the camber by looking at the temperature across the tire. We found a little time on the skidpad made a big difference, made a nicer car. We started setting up all our cars that way. We'd get them all ready to go to a race and we'd go a few rounds in both directions and make sure it was balanced. That was good for slow speeds, about 40 mph, and then we'd go out and run through a high-speed turn, 150 mph, and we'd see how it was balanced. That was the way we set the aerodynamic balance.

"So Firestone told us their tire was built to run on a 7-inch wide rim. I had built some modular wheels and we could vary the width by what mid-section parts we used. We'd run the tires they gave us on a 7-inch rim and maybe an 8 and a 9 too. The wider rims made the sidewalls stiffer and instead of running a 0.95 average G you'd run a 0.99. So of course we put them on 9-inch rims.

"Well, we'd go to the next race and the Firestone guys would look at them and say, 'We didn't design those tires to run on a 9-inch rim. We better build a new tire.' They'd add an inch to the tread. They'd do them quick too. They can build prototype tires in a hurry. In a couple of weeks they'd have another tire. And we'd run it on a 9-inch rim and a 10 and maybe an 11. And we'd find it was better on a wider rim, so it would happen all over again.

"In a matter of less than a year we went from those narrow little Dunlop Green Spots to a tire that was almost double the width. And our single-speed torque converter just couldn't handle all that grip. We immediately went to a two-speed transmission so we could get more torque multiplication off the slow-speed corners.

"So that's what happened with me on tires. In the middle '60s, probably '64 or '65, Firestone took us from less than 6 inches of tread width up to 12 inches."

Paul: "Just because you kept skidpad testing them on wider rims?"

Jim: "Right."

Brian: "Speed is the criteria at the end of the day. Speed on the skidpad is speed around the racetrack."

Jim: "Cornering speed is the key to everything. You can have more horsepower, you can accelerate fast, but you got to stop it at the other end. But if you leave the corner just that much faster, you carry that speed all around the racetrack. The whole thing is cornering speed, basically."

Why Wider Tires Are Better

For the same vertical load and internal pressure, a tire with a wider tread has a shorter, wider contact patch than a narrower tire. The area of both contact patches is the same if the internal pressure and load are the same. In the section on lateral tread deformation we showed that deformation builds up along the length of the contact patch until the restoring force of the tread and carcass exceeds tread grip and sliding begins.

A shorter contact patch at the same slip angle begins to slip at roughly the same distance from the leading edge as with a longer contact patch. But the shorter contact patch has more of its length stuck to the road than the longer, narrower contact patch; and therefore a larger portion of its overall area is gripping. A larger portion of contact-patch area gripping means more total grip. So for the same load and same slip angle, a wider contact patch generates more grip that a narrow contact patch.

This table presents changes in contact patch (CP) length at various tread widths. I'll assume slip starts 1.5 inches into the contact patch. The load on the tire is 500 lb and the tire pressure is 20 psi.

Table 6-1. Gripping Area Calculation

Tread width, in	6	8	10	12
CP length, in	4.17	3.13	2.50	2.08
CP area gripping, %	36	48	60	72

Self-Aligning Torque

All of us have experienced the force needed to turn a steering wheel. Some of us have also felt this force go away when the front tires begin to slide, maybe when driving on a wet road. This schematic explains the source of that force, called the restoring moment or self-aligning torque (SAT).

Fig. 6.13 shows how the lateral force generated by the tire varies along the length of the contact patch. Lateral force starts out at zero at the front of the contact patch, reaches a maximum, and then begins to fall off when the tread starts sliding as the vehicle weight on the tread decreases. After this point of maximum lateral force the restoring forces in the tread structure overcome the tread's grip on the road and lateral force goes back to zero again when the contact patch lifts up off the road.

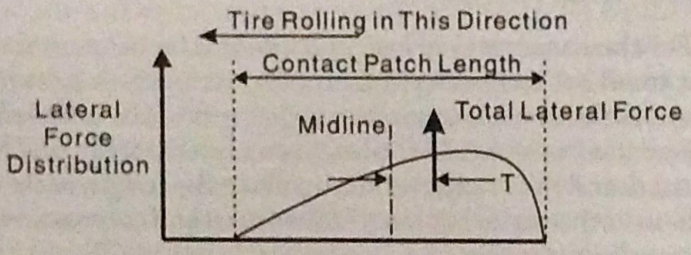

Fig. 6.13 Contact-Patch Forces and Self-Aligning Torque

Notice that the resulting total force (what you get if you add up the magnitude of all the forces at each increment through the length of the contact patch) over the contact patch area is behind the midline of the contact patch. Since that total force is working a distance "T" from the contact patch midline, there is a counter-clockwise torque, also called a moment, trying to rotate the tire away from its steer angle. In the schematic, the steering angle is to the right or clock-wise. This torque is called the restoring moment or self-aligning torque.

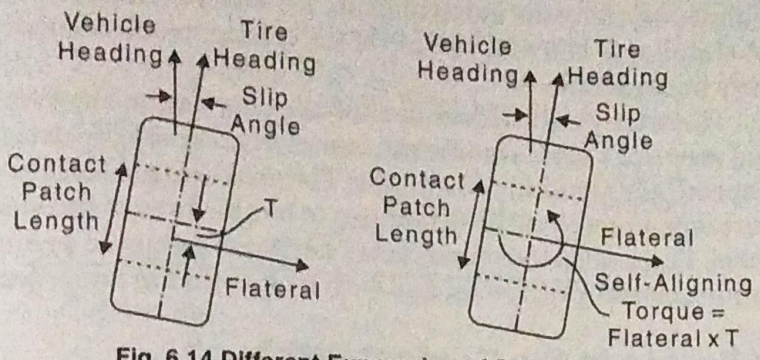

Fig. 6.14 Different Expression of Same Forces

Fig. 6.14 shows two schematics expressing the same phenomenon in two ways. In the left-hand schematic the tire lateral force is acting at some distance behind the center of the contact patch. We can make another equivalent schematic on the right showing that same lateral force through the center of the contact patch plus a torque on the tire. Flateral acting through the center of the CP and the moment have the same effect on the tire as the Flateral offset from the CP center. This schematic illustrates the source of what we all feel when we steer a car, a lateral force that turns the car and a restoring moment resisting steering wheel movement.

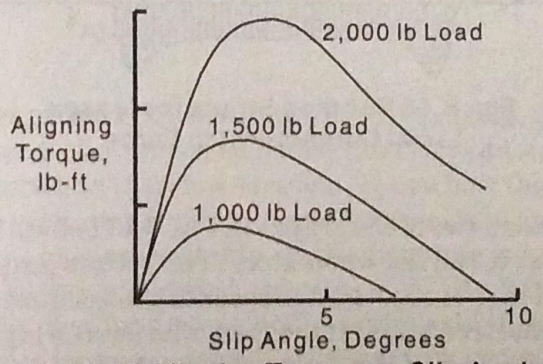

Fig. 6.15 Aligning Torque vs. Slip Angle for Three Vertical Loads

The curves in Fig. 6.15 show how self-aligning torque, SAT, varies with slip angle and vertical load. The general shape of the curve, increasing and then falling off at higher slip angles, tells us what we feel as we corner a car harder; steering forces go up and then fall off as the rear portion of the contact patch begins to slide.

The reason for a smaller SAT at higher slip angles is more sliding farther forward in the contact patch. Because of this the total force generated in the contact patch moves closer to the contact patch

midline, reducing the moment arm, "T." The total lateral force is higher but slippage in the rear portion of the contact patch reduces the restoring moment.

These curves also show us that aligning torque increases as tire load goes up. This is significant, especially on racecars designed to generate aerodynamic downforce. The goal is to get more grip with more downforce, but the driver has to be able to turn the steering wheel. Front-suspension geometry has some influence on aligning torque and steering forces, and we'll look at that in later chapters.

Vertical Forces in the Contact Patch

Fig. 6.16 shows how bending stiffness in the tread and sidewall plies increases contact-patch forces at the outside edges of the tread. If you've ever left your tires underinflated for a period of time you noticed increased wear in these areas. Proper inflation pressure supports the tread area and evens out this force distribution.

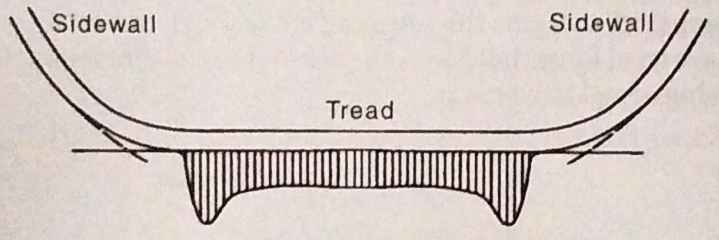

Fig. 6.16 Bending Stress Increases Local Contact-Patch Force

You've seen two of the graphs in Fig. 6.17 before, but they all need to be together to tell the whole story. The bottom graph shows how vertical load in the contact patch reaches a maximum quickly and trails off as the tread lifts off the road. The force is higher at the front of the patch because of tread momentum; the tread is slapping down onto the road.

Another way to look at this is to think of the tread as a continuous belt. The tread has to change direction as it comes into the contact patch. The sidewall compresses in this area because the tire has a loaded radius smaller than the free radius. As the tire tread rotates into the contact patch it has some vertical velocity relative to the road. As the tread slows down with respect to the ground it gives up some momentum that translates to the tread pushing on the road at the front of the contact patch. There is a corresponding decrease in force at the rear of the contact patch and this pressure distribution becomes more exaggerated with speed.

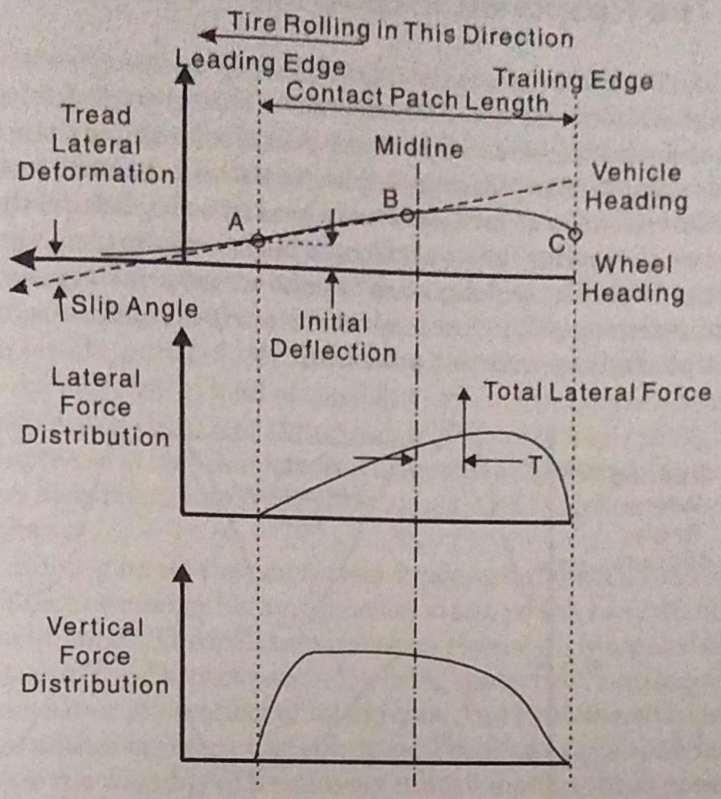

Fig. 6.17 Contact-Patch Forces

Under extreme acceleration as in drag racing, the rear tires reach a high level of slip, and tread momentum can add significantly to the vertical force and therefore traction. That's how those top-fuel dragsters get so much grip and acceleration. And once again tires show their amazing flexibility. As the dragsters gain speed the tire diameter grows, generating a gearing effect that allows high speeds without the need for a transmission and gear shifting.

Another interesting result of momentum transfer at high speed is increased ride height and a higher tire spring rate. The momentum the tread gives up, results in a force upward on the tire which can raise the tire enough to affect the ride height of the racecar. This can be significant on ground-effect cars. We'll examine this point in a later chapter.

Dynamic Tire Response to Steering

Fig. 6.18 comes from data taken from a passenger car driven through a slalom course. It shows how steering angle, lateral acceleration, and steering-wheel force vary over the length of the course. The speed is about 30 mph and pylon separation is about 65 feet. You can see that lateral force and steering wheel force lag behind the steering wheel angle. A time delay also exists between lateral acceleration and steering force. These delays are dependant on a variety of variables, including car speed, pylon separation, surface conditions, tire construction, and tire-inflation pressure.

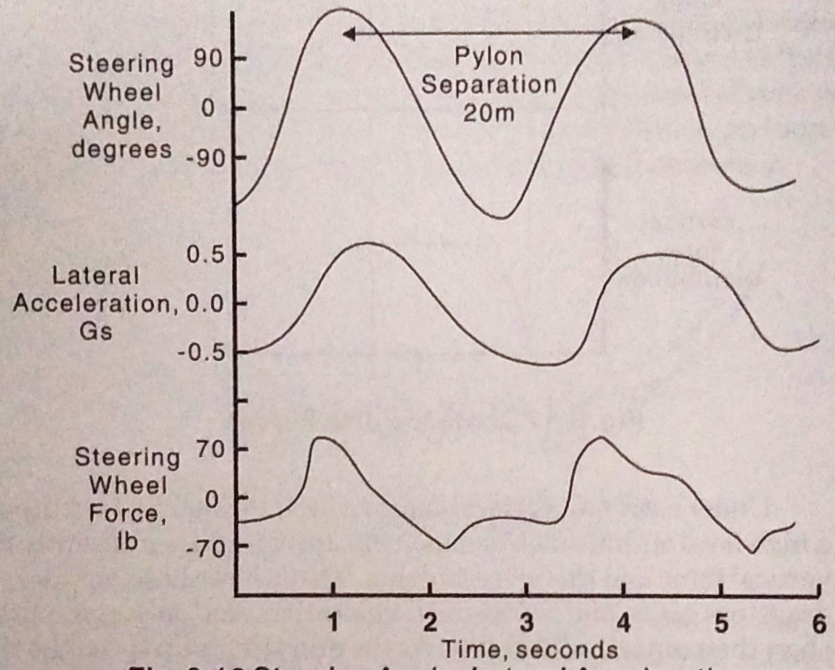

Fig. 6.18 Steering Angle, Lateral Acceleration, and Steering Force for a Car in a Slalom

A passenger-car driver almost always perceives a tire with less time delay between steering and lateral acceleration as more responsive. In general the same can be said for racecar drivers and racing tires, but the variables are much more complicated because control at the limit of adhesion and feedback from the tire/suspension/chassis to the driver is extremely important.

While at a media event at the Indianapolis Motor Speedway I rode as a passenger with Buddy Lazier driving a couple of fast laps in one of the Chevrolet Corvette Indy 500 pace cars. He braked hard from about 140 mph as he steered into the turns, and it seemed to take forever for the car to stop moving sideways. I didn't notice the straight-ahead speed all that much but the lateral movement got my attention.

Rolling Resistance

We know now that a load distorts the structure of a tire in the contact patch where the tire comes in contact with the road. Since a tire is a composite of textile cords in a rubber matrix covered with a rubber tread and we know rubber absorbs some energy when deflected by a force, we can expect that a rolling tire would absorb some energy. In a simple rolling tire this is called rolling resistance and it increases with speed and load. The most important factor(90%-95%) in power consumption of a tire is the degree of hysteresis in the rubber compounds, particularly that of the tread compound.

An increase in load at constant internal pressure and constant speed causes more tire distortion, which increases rolling resistance. An increase in inflation pressure at constant load and speed results in lower distortion, less hysteresis losses, and therefore lower rolling resistance.

Rolling resistance increases exponentially with road speed. As the tire absorbs energy its temperature rises, which has two favorable consequences. The inflation pressure rises with temperature, reducing the size of the contact patch, lowering distortion, and lessening the power-absorption effect of hysteresis. And hysteresis in rubber goes down with increasing temperature. These two favorable factors reduce the possibly of a runaway failure mode at high speed.

Radial tires have tread areas that are more stiff and stable than bias-ply tires and they have less distortion in the contact patch, resulting in less rolling resistance. Wider wheel rims lower distortion in the tire and the shorter sidewalls needed on wider-aspect-ratio tires that are used on larger-diameter wheels also generate lower tire losses because of a flatter, more stable tread area.

Induced Drag

You don't get something for nothing, and tire forces are no exception. A tire at some slip angle generates a force that accelerates the tire/wheel/car toward the center of an arc and turns the car around the corner. You can see in Fig. 6.19 that Fcentripetal is perpendicular to the vehicle heading. But, if you look at the lateral force from the perspective of the tire itself, you have to resolve Fcentripetal into Flateral, perpendicular

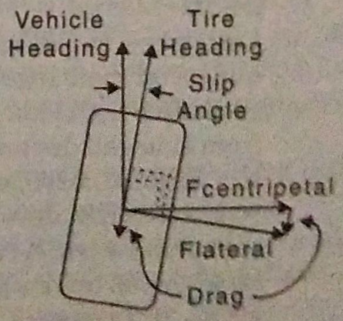

Fig. 6.19 Drag Induced by Slip Angle

to the tire centerline, and Fdrag. We can move Fdrag over to the tire centerline to more easily understand its result—a force that has to be overcome to keep the tire rolling at a constant speed.

If you remember your analytical geometry and trigonometry from high school or college, you recognize that these three forces make a right-angle triangle and drag can be calculated by multiplying the lateral force times the sine of the slip angle.

This is called induced drag because it is analogous to the induced drag of a wing caused by aerodynamic lift and the angle of attack of the wing. No matter the details of rubber compounding and construction making up a tire, induced drag goes up with slip angle and lateral force.

Radials Are More Efficient

Radial tires are more difficult to manufacture than bias-ply tires. The U.S. tire industry resisted making radials for a long time after it was obvious they provided a major improvement in performance, mainly lower rolling resistance. Lower rolling resistance causes less heat generated in the tire. Depending on the application, a radial tire can have a softer compound and get better grip with the same wear as a bias-ply tire or produce better wear and last longer with the same grip as a bias-ply.

Because the reinforced tread area of a radial tire results in a flatter, stiffer contact patch, you get higher restoring forces at lower values of lateral tread distortion, which translates to smaller slip angles for the same lateral force as bias-ply tires. The smaller slip angles mean less induced drag.

Bias-ply tires usually have the same number of plies in the sidewalls as in the tread area. But radial tires can have thinner, more flexible sidewalls (two plies) and the tread area is beefed up with extra plies, called belts. The result is a flexible area where the sidewall and tread come together which acts as a hinge when a radial tire generates high lateral forces. This hinge partially decouples the tread from sidewall distortions, creating a more stable contact patch.

When Goodyear switched NASCAR Winston Cup tires to radial construction in the early 1990s the teams had difficulties making their old setups work. A radial race tire generates more lateral force at smaller slip angles and sideforce falls off quickly after the top of the curve. Drivers were used to operating at high slip angles with the bias-ply tires and the tires gave more warning at breakaway, so they were easier to drive at the limit. And softer sidewalls and stiffer tread belts make radial tires more sensitive to camber. Generally it takes more camber to generate significant camber thrust with a radial tire.

After the change to radials, drivers found it was more difficult to drive near the limit of adhesion. Racing magazines begin to have help-wanted ads for crew chiefs with "radial tire experience." As usual, the teams that were asked to perform the testing for the tire companies adapted with fewer problems.

Camber Thrust

Current race- and street-car suspension-design practices allow fairly precise control of the instantaneous attitude of the tire with respect to the chassis and even with respect to the road. Camber is one suspension adjustment that can get more grip from almost any tire and, therefore, it gets a lot of attention from racecar designers and race engineers.

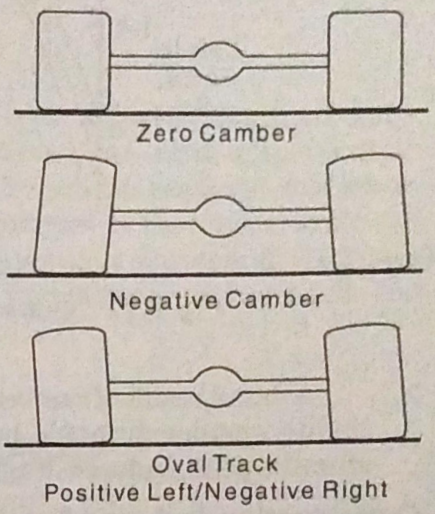

Fig. 6.20 Camber Variations

As shown in Fig. 6.20, negative camber is defined as the tops of tires on the same axle being closer together than the bottoms of the tires. The effect on the loaded contact patch is shown in Fig. 6.21. More load on one corner of the tire and less on the other results in a trapezoidal contact patch shape. The leading edge of the contact patch is turned toward the camber lean and, as the tire rolls forward, the leading edge comes down onto the road with a slip angle even though there is no steering input. Just like a tread on an armored tank, the rest of the tire tread follows this leading edge. As a result the tire produces some lateral force even if the actual steering angle is zero.

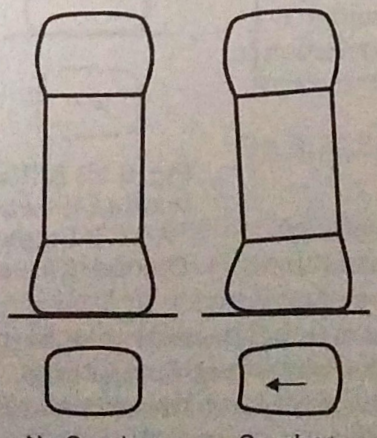

Fig. 6.21 Camber Distorts Contact Patch

Contact patch interaction with a road is complicated, but negative camber reduces sidewall roll-under due to lateral force and allows a more even load distribution in the contact patch. The observed benefit of camber is it produces

extra lateral force without a significant increase in tire temperature. Fig. 6.22 is a graphic representation of camber thrust.

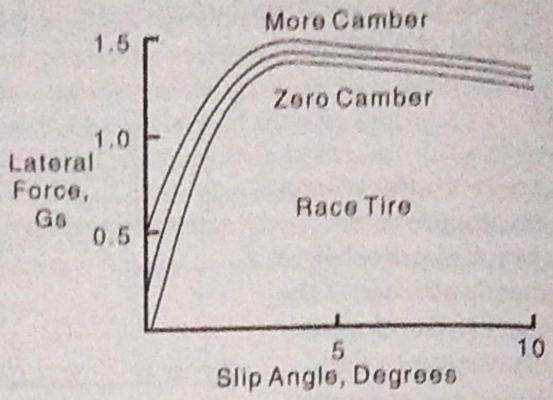

Fig. 6.22 Camber Increases Side Force

A detail result of camber is that the lateral force peak occurs at a slightly smaller slip angle, but lateral force also falls off more quickly after the peak. Induced drag is also reduced at maximum grip.

Construction-Induced Camber

NASCAR mandates rear-axle housings that limit camber on the rear tires to about a half a degree. But tires can produce camber thrust without a camber angle. The schematic in Fig. 6.23 shows how a stiff inside sidewall generates contact patch distortion similar to wheel camber. The outside sidewall has a lower spring rate and deflects more, producing a trapezoidal contact patch and more even load distribution in a corner

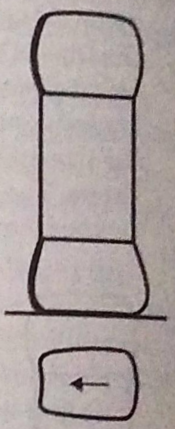

Fig. 6.23 Stiffer Inside Sidewall Also Causes Camber Thrust

Stagger

Cars racing on oval tracks only make left turns. To help the cars turn, tire manufacturers make rear tires of different diameters and mount the big one on the outside. Since rules mandate a solid rear axle (no differential action), the outside rear tire wants to go farther each revolution than the inside tire, creating a torque on the car toward the left. When racers used bias-ply tires, they could overinflate the tires and stretch them to the desired stagger. As you can imagine, some people were better at this than others.

Radial tires are manufactured to a specific diameter within a small tolerance and can't be stretched. Stagger values range from 0.2 to 0.5 inches in circumference for high-speed ovals on pavement to half a foot for cars racing on dirt ovals.

An interview with Mario Andretti later in the book reveals some surprising events in the development of stagger.

Internal Pressure

The inflation pressure of a tire is perhaps the most important variable that, given a specific tire, a racer can use to influence the tire's performance characteristics. By now the reader should know that it's the internal pressure counteracted by the tension in the carcass, a torodial pressure vessel, that actually supports all loads applied to a tire. So it should be no surprise that inflation pressure influences tire performance. But it's complicated.

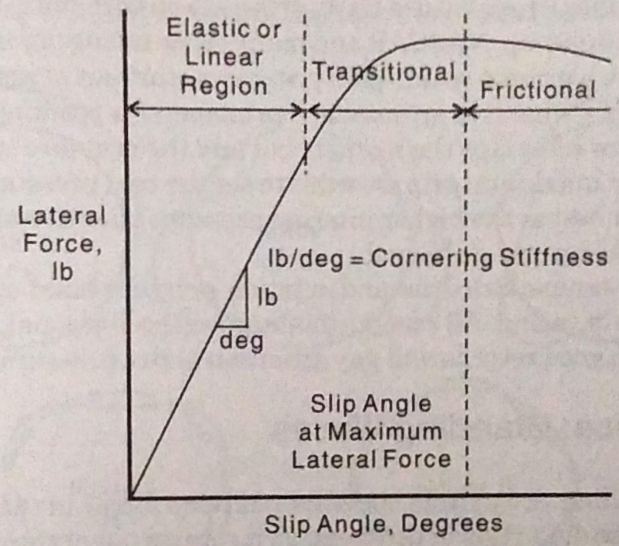

Fig. 6.24 Side Force vs. Slip Angle

Have another look at this graph in Fig. 6.24 showing the relationship between slip angle and side force for a generic tire. In the linear area of the curve the slope of that curve is mainly determined by carcass/tread stiffness; the stiffer the tire the more lateral force for a given slip angle. Further up the curve, however, where more of the contact patch is slipping on the road, friction between the tread and the road is the dominant factor determining grip. So at smaller slip angles an increase in tire pressure stiffens the carcass and the tire generates more grip for a given slip angle.

But at higher slip angles, higher inflation pressure decreases contact patch area. With less rubber in contact with the road, friction force decreases and sliding increases. This reduces grip and increases frictional heating, further reducing grip.

In racing it's ultimate grip at maximum slip angles that matters. During NASCAR Winston Cup races on TV, reporters cover pit stops in great detail, telling us about changes made to improve handling, including tire-pressure changes. A decrease in right-front tire pressure by one pound increases grip on that tire by increasing contact patch area and could help cure an understeer condition. But, as always, there's a trade-off. The lower inflation pressure reduces tire stiffness and the tire doesn't feel as responsive to the driver at corner entry. The best drivers aren't spooked by a sloppy feel at turn-in, if they get more ultimate grip.

A tire is a spring and the spring-rate of a tire is mainly due to its internal pressure. In later chapters we'll discuss diagonal weight transfer—wedge—and how tire inflation pressure affects handling.

Another tire-pressure trade-off has to do with temperature and pressure build-up. NASCAR and many other racing organizations forbid tire warmers so inflation pressures start out at ambient temperatures—whatever an outside thermometer is reading at the time. After a few hard laps the tire gets hot and the pressure inside the tire rises. For maximum grip we want to set the cold pressures so the tires will work best at the higher internal pressure after tire temperatures have come up and stabilized.

Tire-temperature rise and inflation-pressure build-up happens in all forms of racing. All racers, amateur and professional, have to maintain good records and pay attention to tire pressures.

Tire Dynamics: Standing Waves

A rolling tire at high speed can develop forces in the contact patch that cause distortion of the tread as it rotates out of the contact patch. When this condition is reproduced on a test drum the distortion is stationary to an observer and is called a standing wave. High-speed rotation prevents tread and sidewall distortion in the region of the contact patch flat spot from blending smoothly into the unloaded shape of the tire. Instead, contact patch distortion persists, recovers, overshoots, and recovers again with decreasing amplitudes until completely damped. Standing waves are damped out before they get back around to the contact patch and so do not propagate around the circumference of the tire.

As you might imagine, a standing wave creates considerable heat and stress in a tire, but modern tires, both road and race, have relatively stiff structures, eliminating standing waves with normal operating speeds and inflation pressures.

Frequency Response

Experimenters in this field have determined that rolling tires behave closely enough to stationary tires in frequency-response tests that most of the data available comes from tests of tires statically loaded on a vibrating platform. Tires respond to forced vertical vibrations by deforming in harmonic modal patterns. The graphics in Fig. 6.25 presents the first five vibration modes and their frequencies.

Irregularities and bumps in a track surface can easily drive a tire into one of these modes if the track surface supplies the correct disturbance frequency. The reinforcing belt under the tread of a radial tire has a butt splice or overlap splice. An easy calculation reveals the frequency of a splice passing through the contact patch is 40 hz

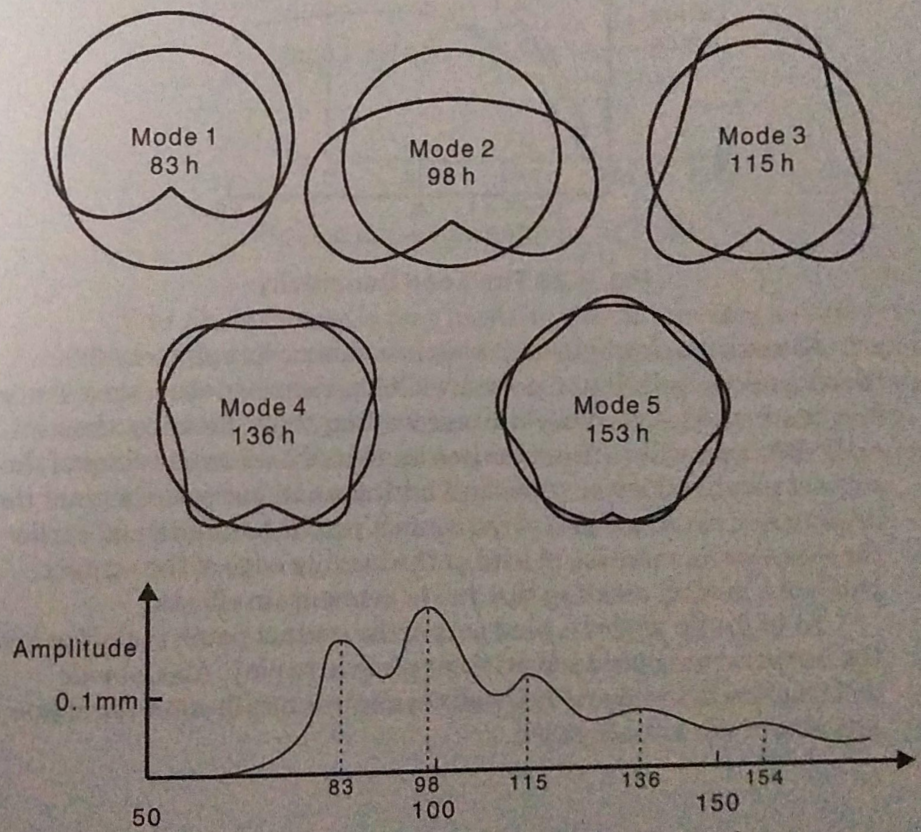

Fig. 6.25 Vertical Frequency Response, h

(cycles/sec) at 200 mph for a tire with a 28-inch diameter. There is the possibility for this splice, or any other defect or irregularity in the tire, and/or any disturbing vibration coming from the car or the track surface, to supply a self-energizing forcing vibration. Obviously a smaller tire raises that passing frequency and a larger tire decreases it.

Load Sensitivity of Tires

In Chapter 3 we found that rubber friction has several components, the most important being adhesion and deformation. With increasing load the total coefficient of friction between rubber and a rough surface increases, but at a decreasing rate. Rubber is sensitive to variations in load, temperature, sliding speed, and surface texture. Fig. 6.26 shows lateral force vs. slip angle at three loads.

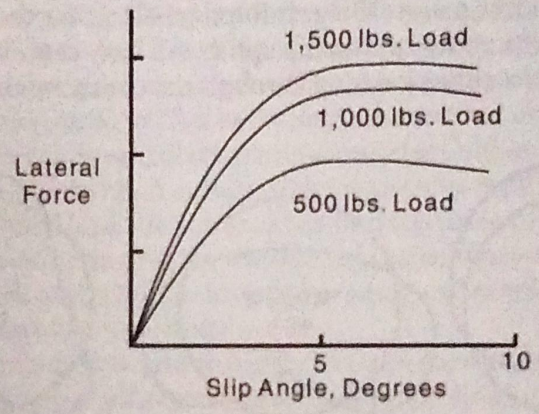

Fig. 6.26 Tire Load Sensitivity

Actually the load-per-unit area in a tire contact patch is determined mainly by inflation pressure. Changes in load result in a change in contact-patch area while the unit loading stays the same, theoretically. But sidewall stiffness causes increased load on the sides of the contact patch. Likewise tread/belt stiffness can increase forces at the leading and trailing edges of the contact patch. As mentioned earlier there is also an increase in load at the leading edge of the contact patch of a loaded, rotating tire due to momentum effects.

At high slip angles a good part of the contact patch is sliding and the temperature/speed sensitivities come in to play. Also, elastic deformation in tread and sidewalls can substantially alter the shape and size of the contact patch.

And here's another factor that changes with load that affects grip—contact patch length. As described earlier in this chapter, a wider, shorter contact patch produces more grip because less of the contact patch is slipping at the same load and slip angle. But an increase in load lengthens the contact patch, increasing the sliding portion and decreasing grip.

So there are several factors that add up to the fact that tires are sensitive to applied load. Think of it as an efficiency phenomenon. Fig. 6.27 shows a graph of lateral force vs. load. Values of lateral force increase in diminishing increments as load increases in equal increments.

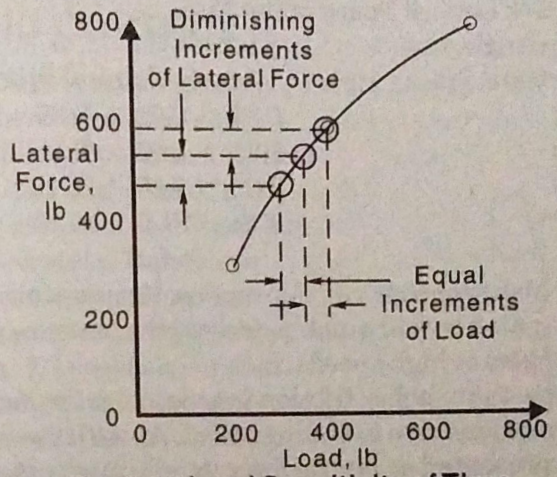

Fig. 6.27 Load Sensitivity of Tires

This phenomenon is very useful in that it provides us with an extremely sensitive adjustment for relative grip between the front and rear wheels of a vehicle. On both racecars and street cars, front/rear spring-rate distribution, cross-weight, and anti-roll bars can easily adjust oversteer and understeer, referred to as balance. We'll examine this in more detail in a later chapter.

Lateral Speed of the Tire

In the chapter on rubber friction, we learned that friction forces in rubber vary with sliding speed and temperature. A tire rolling at some slip angle generates a lateral component of speed that is proportional to the slip angle. Even though the rubber in the contact patch is stuck to the road at low slip angles, the contact patch, indeed the entire tire, has this component of lateral speed. At higher slip angles a good part of the contact patch is actually sliding against the road surface. The following table uses the sin of the slip angle multiplied by the speed of the vehicle to calculate the lateral speed of the tire.

Table 6-2: Lateral Speed of the Tire

Slip Angle, deg	1	3	5	7	10
Forward Speed, mph	Lateral Speed, mph				
50	0.87	2.62	4.37	6.14	8.82
100	1.75	5.24	8.75	12.28	17.63
150	2.62	7.86	13.12	18.42	26.45
200	3.49	10.48	17.50	24.56	35.27

At the higher speeds and slip angles, temperature generation in the contact patch would quickly destroy the tires, so you don't see large slip angles at high speeds.

We know that rubber friction is a viscoelastic phenomenon and therefore very sensitive to sliding speed. As we'll see in a later chapter, tire data is presented as lateral force vs. slip angle. But this data comes from a machine rotating the tire at a relatively slow speed and few test machines are robust enough to take data on race tires at high slip angles.

I'd guess that at higher speeds there is not so much an optimum slip angle as there is an optimum lateral sliding speed. And, if that is true, there is an optimum slip ratio for forward drive.

"It will be nice working with a good driver again. The world is a cheerier place when the tires get warm."

—Alec Purdy, race engineer.

CHAPTER 7

BALANCE AND CONTROL

Racecar drivers, engineers, and TV race analysts are constantly talking about balance. They use words like "tight" and "push" for understeer, and say "loose" to describe oversteer. Balance is critical to understanding how efficiently a car is using its tires.

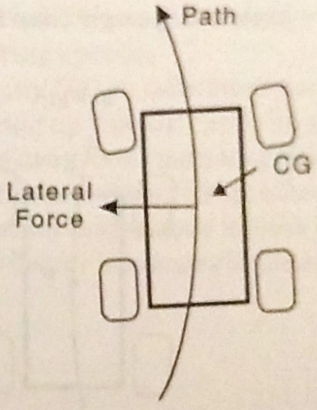

Fig. 7.1 Car on a Circular Path

In Fig. 7.1 we see a car that has steered into a corner and maintains a circular path. The front tires have a slip angle and the chassis has rotated so the rear tires also have a slip angle. The car is not spinning so we know the forces on the car are balanced. The torque or moment created by the force of the front tires times their distance ahead of the car's center of gravity (CG) balances the rear-tire forces times their distance behind the CG. As a result the front and rear tire forces can be combined at the CG and called lateral force. But the front and rear tires might need different slip angles to achieve this balance. The relationship between the slip angles at the front and rear tires is what determines balance.

Oversteer and Understeer

The best way to define these terms is to start with neutral steer. This is the condition where a driver of a car in a corner does not have to change the steering angle when the car changes speed. A neutral-steering car that is not already at maximum grip for that corner can speed up and maintain the same radius path with no change in steering. Extra forces needed from the front and rear tires at the higher speed cause those tires to go to identical but higher slip angles than were required at the slower speed. We say the car is balanced or neutral.

Understeer happens when, in that same constant radius turn, the driver has to increase the steering angle (turn the steering wheel into the turn) as the car speeds up. The extra force needed to keep the car at that radius at the higher speed causes the front tires to go to a higher slip angle than the rear tires, as shown in Fig. 7.2.

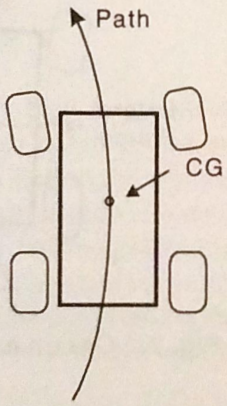

Fig. 7.2 Understeer

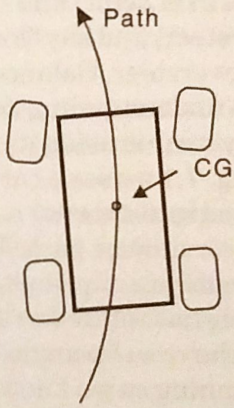

Fig. 7.3 Oversteer

Oversteer occurs when the rear tires go to higher slip angles than the front tires as the car speeds up. This is not a stable situation, and that's why most street cars are designed with a mild understeer condition. The inherent instability of oversteer is due to the fact that front and rear wheels are connected together by the chassis, and if the rear tires go to a higher slip angle the front tires do also. This increase in front steering forces the car into a sharper turn, causing even higher slip angles at the rear. Unless the driver steers into the slide, as in Fig. 7.3, the car spins out of control.

Consequences of Imbalance

When a car is balanced—close to neutral steer near the top of the side-force-vs.-slip-angle curve—both front and rear tires are at the same slip angle so they are generating maximum grip under those conditions. A car that is not balanced—it's understeering or oversteering—has one set of tires operating at less than maximum slip angle and the car is not generating the maximum potential lateral force.

Additionally, a tire operating at any slip angle generates an induced drag, described in the last chapter, that increases with slip angle. The front tires on an understeering car are operating at a higher slip angle than if the car was better balanced. That higher slip angle means more induced drag and it can slow the car in a corner. This becomes most important for racecars on high-speed ovals where speed in the corners is engine-power limited. The engine has to overcome tire drag, so tire drag lowers cornering speeds.

When you watch qualifying for the Indy 500 on television you hear drivers and engineers talking about "freeing up the car." They're saying the car setup has been changed to reduce drag, both aero and tire drag. They try to reduce understeer and the associated drag, allowing increased speed in the corners. Of course less understeer means the car is closer to oversteer, which gives the driver less margin for error. Life is full of trade-offs.

The Driver Is Important

"Freeing up the car" only works if the driver is able to drive close to the limit of grip with less understeer. Andy Brown, race engineer with the Panther Racing Indy Racing League team, says his driver, Sam Hornish Jr., is one who can.

"He raced in karts for a long time and Atlantics just a year," Andy told me after Sam won two races early in the 2002 season. "He caught on to these cars very quickly. In low-grip situations he can get closer to the limit than most drivers. He likes the car closer to neutral balance, and that means we can trim the drag, both aero and mechanical. If you watch his hands during in-car camera shots there's much less movement than other drivers. He's rock-steady."

On the other end of the scale was Mark Blundell, Formula 1 and CART driver. I traveled with the PacWest CART team in 1997 researching a book I published called *Inside Racing*. Mark won three races for PacWest that year, but he constantly talked about the rear of the car being "nervous." At the high-speed oval at Michigan he complained

that the rear of the car was "walking." Between track sessions I talked to his engineer, Allen McDonald, about the walking and the importance of balance at a track like Michigan.

"Here at Michigan you're in the turns for most of the lap," Allen told me. "Mark's 'walking at the rear' problem is him correcting for oversteer and then turning again. He won't admit it but he really doesn't like an oversteering car. It gets into a feedback loop all through the corner. He says it's pushing, but the rear is walking. If he'd let the rear of the car take a set like Mo [PacWest's other driver, Mauricio Gugelmin] does, he'd be faster."

I repeated what I thought Allen was saying. "So if the car is balanced, then the front and rear tires are at about the same slip angle. In that condition there's less scrub than if that same car is pushing."

"Yes," Allen said.

To explain in more detail, Mark was feeling the rear of the car move as the rear tires tried to go to a slip angle that would produce the lateral force necessary to keep the car in the turn. Mark didn't have the confidence that there was a limit to the movement he felt so he steered into the turn to correct his perceived oversteer. Allen had to dial in some understeer to keep Mark from feeling the rear move. Compared to Mauricio's car, Mark's front tires were at a higher slip angle and produced more drag for the same lateral grip. His rear tires were at a smaller slip angle and weren't generating as much lateral grip as Mauricio's. Mark's car also had bigger Gurney flaps and higher angles of attack on the wings. The result was slower lap times.

What the Tires See

Let's say we've got a perfect car that has equal weight on all four tires and the front and rear suspensions are using the tires almost identically. As explained before, slip angle is the difference between where the tire is pointed and where it's actually going. A tire has to have a slip angle to make a side force, and side force is what keeps a car going in a curved path.

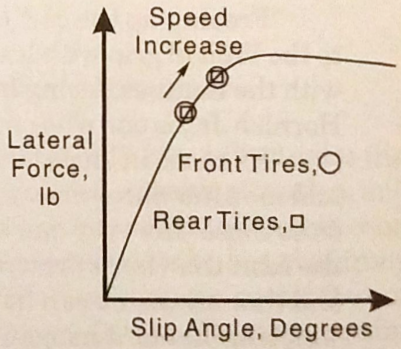

Fig. 7.4 Neutral Steer

The graph of lateral force vs. slip angle in Fig. 7.4 shows a balanced car with front and rear tires moving together to larger slip angles as the driver increases speed in the turn. The larger slip angles produce higher lateral forces, but are balanced so the driver doesn't have to turn the steering wheel. A balanced car can corner faster

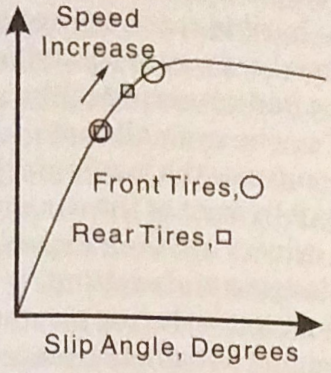

Fig. 7.5 Understeer

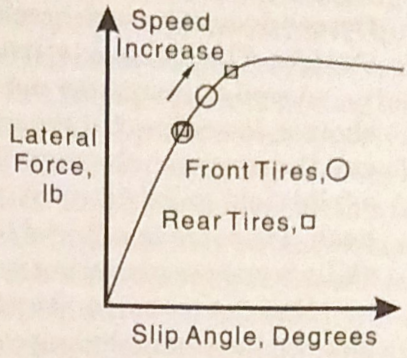

Fig. 7.6 Oversteer

because both the front and rear tires get to the top of the curve at the same time, and they generate more combined side force than if one had reached the top ahead of the other.

In Fig. 7.5 the car is not balanced. The front tires start out at the same slip angle as the rears but go to a higher slip angle with increased speed. Once the tires are past the top of the curve they don't gain lateral force with more steering. The rear tires don't get up on the curve as far as when the car is balanced, so the total lateral force produced by the four tires is less and the car corners slower. The driver can reduce throttle and slow the car or reduce steering and let the car go to a bigger radius corner.

If the rear tires get to maximum lateral force first, as in Fig. 7.6, you have oversteer and the car can spin out of control. A skillful driver can steer into the slide, decreasing the front-tire slip angles and avoiding a spin. This causes the car to go to a larger radius curve, however, and the car might go off course or hit a wall.

Again, Drivers Can Make a Difference

The importance of balance really stands out when you see a NASCAR race at the Atlanta Motor Speedway. This track has very long corners and relatively short straights. The cars are in the corners for more than half of the time for each lap, so an imbalance shows up dramatically.

A good driver can alter style or line to accommodate an unbalanced car. A Winston Cup driver at Atlanta might drive higher up the track in the corners to compensate for an understeering car. The larger radius needs less steering input and maintains a higher speed than a car in the lower, tighter line. The higher line needs less steering angle and the smaller slip angle at the front means less induced drag and

less heat build-up in the right-front tire. Corner exit speed is higher so the car doesn't have to accelerate as hard to reach top speed on the straight. The problem is that's not the short way around the track.

A well-balanced car can pass the understeering car by using the shorter, lower line but the trade-off can be so small that the two cars exit the corner on the same line. Sometimes the low-line driver can do a "slide job" and drift up at corner exit in front of the car with the push. These trade-offs and how the drivers use their experience and skills is one reason racing is so challenging and exciting.

Race teams can make a few adjustments during pit stops to help balance the car, including corner weight (wedge), tire pressures, and Panhard bar height. These adjustments affect mechanical grip, but on open-wheel cars there are also ways to change front-wing angle of attack and rear-wing Gurney flaps to balance the car aerodynamically at higher speeds. We'll look at the mechanical adjustments in a later chapter. The goal is a balanced car that can operate controllably with both tires at the top of the side force/slip angle curve, generating maximum grip and maximum speed in the corner.

Control at the Limit of Adhesion

As stated earlier, a car in a corner under steady-state conditions is stable or it would spin. If the car speeds up and maintains that balance the car is called neutral steer. When the car speeds up and the front tires go to a higher slip angle than the rear tires, the car is said to understeer. The opposite condition, oversteer, occurs if the rear tires go to a higher slip angle than the front tires as the car gains speed. These different conditions are of no consequence as long as the tires are operating in the linear portion of the side force vs. slip angle curve. Tire stiffness, determined by design but adjusted by tire pressure, determines the slope of the curve in this area.

But things change when the tires are operating at their maximum level of grip and most of the contact patch is sliding. The pair of tires (front or rear) reaching the limit first give up control. The front tires of an understeering car at the limit are operating at a high slip angle and more steering earns no extra grip. The rear tires, however, can still go up the curve, but there is no steering wheel for the rear tires.

But the driver also has a throttle! Due to the friction circle phenomenon an increase in driving force at the rear tires dictates an increase in slip angle for those tires. So an understeering car at the limit can use the rear tires better with the careful addition of some throttle. Or the driver can carefully let off the throttle and the car will slow down, regaining front grip and control.

Actually an experienced driver cursed with an understeering car might perform a combination of control inputs in the corner. A quick lift on the throttle slows the car shifting some weight from the rear tires to the front tires, generating some front grip. Then getting back on the throttle can generate some rear-tire slip angle without driving the front tires too far over the top of the curve. Skillfully executed, this maneuver can go through the transient instability and result in a faster, better-balanced car. Deft use of the throttle can help balance a car.

If the rear-tire pair gets to the top of the curve first, control is also lost at that end. The throttle doesn't help anymore, but the driver can still control the car by letting out steering input to save the spin and letting the car go to a larger-radius turn.

A neutral-steer car is the holy grail of all racers even if it has to be tuned back to slight understeer for safety in a high-speed turn. At the limit of grip both pairs of tires are operating at maximum adhesion and neither has control. Stirling Moss, the legendary mid-20th century race driver, is quoted as saying that a car set-up for maximum cornering power is "like a thrown dart" as soon as the driver has committed to the corner. The best drivers are able to inject small control efforts with changes in throttle and steering, but if the car is at the limit it is uncontrollable from the time the driver turns in until steering is paid out at corner exit.

I have no personal experience driving at this level but I'll bet it was a lot easier in the '50s on those narrow, bias-ply tires than it is today on high-grip, wide, radial tires.

So Tight It's Loose

While watching racing on TV, you may have heard a NASCAR driver say, "The car's so tight it's loose." Fig. 7.6 shows what happens when the driver of an understeering car goes into the corner and turns the steering wheel far enough that the front tires are on the other side of the peak in the curve. As the front tires go over the top, the rear tires gain a little more side force, giving the car more total grip and more corner speed, but the driver has to be careful at the exit of the turn. Good drivers know about this situation and handle it.

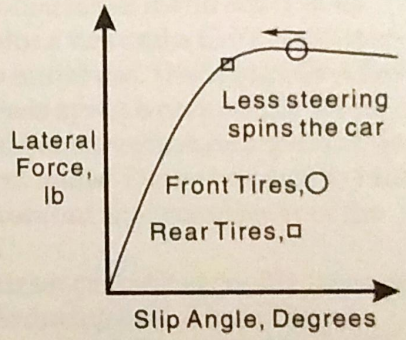

Fig. 7.7 So Tight It's Loose

Normally, coming out of a corner onto a straight, the driver decreases the steering angle and gets on the throttle. But in this case less steering causes the front tires to go backwards up the curve to a smaller slip angle, where they make more lateral force. The rear tires

go back down the curve making less side force, and the car can go to oversteer and snap spin. In the middle of the turn the car is balanced but the car is not stable. The driver may be complaining that the car was loose coming off the corners, but really it was tight—so tight it's loose.

Some drivers like to have a piece of tape wrapped around the steering wheel at the 12 o'clock position so they have a marker that tells them how far they're turning the front wheels. This gives them an easy way to limit how much steering they put into the car. Or, if they have steered the car over the top of the curve, they can anticipate the snap oversteer and drive through it.

"I know the tire companies would like us to believe that heat is the enemy and that anything past three heat cycles will make you slow. From my current experience, after 15 heat cycles you no longer pick up stones in the paddock so it's a lot easier to keep things clean."

—Driver comment from an online forum for club racers, August 2001.

CHAPTER 8

RACE TIRES

Break-In

The critical parts of an automobile engine are made of metal and they maintain their shape in service. Even so, engines made only a few decades ago required a break-in period so parts in moving contact could wear into a close fit without breaking. The wide availability of computer-controlled machining today allows tighter tolerances that pretty much eliminate any need for running in engines built in the last few years.

By now the reader should have some appreciation for the complexity of a tire. Tire components—plies, belts, beads—can't be manufactured precisely as can the computer-machined metal parts in an engine. So an initial break-in period helps a tire and a tire's characteristics might change slightly during this initial use. During the first few miles the chemical used as a mold-release agent wears off the tread surface. The mold vents, those little rubber threads sticking out of the tread rubber, also wear away in the first miles. The carcass cords relax into position and the tread wears to a contour that compliments the car's suspension and the driver's style.

A tire manufactured for use on a street car isn't as highly stressed as a race tire, but it deserves some care during initial use if for no reason other than it is critical to our safety and the performance of the car. It's just smart to check the pressure in new street tires as often as daily for a week or so, and sliding the tire on pavement should be avoided. A daily inspection would also detect any gross manufacturing defects, which although rare, do happen but usually show up early in the tire's life. You don't want to discover a tire problem at 70 mph on a crowded freeway.

Scrubbing Race Tires

As we described in the chapter on design and manufacturing, a tire is constructed of layers bonded together and each layer is made up of stiff cords encased in a relatively supple rubber matrix. And we know that rubber is a viscoelastic material containing complex systems of long-chain molecules connected by entanglements and chemical bonds called crosslinks. Competition tires can see very high temperatures and forces during initial use and local stress concentrations can cause some of the weaker bonds and entanglements to shift, stretch, or break. New bonds may be established. Energy absorbed by these movements actually cause some of the heat that raises the temperature of the tire during this first duty cycle. If this first run on the track is too long or stress concentrations too high, even some of the stronger bonds might be broken, reducing the tire's grip and wear potential.

Running new tires through an easy initial heat cycle called "scrubbing" allows the rubber and cords to settle together more uniformly and relaxes some of the high-stress areas. The tires become more resistant to stress the next time they are used. After scrubbing, tires need a minimum of 24 to 48 hours to relax and reform the stretched and broken bonds. As an absolute minimum most race-tire manufacturers recommend a few laps at less-than-race speeds to condition a tire before it sees maximum stress.

Since some tire-tread compounds are very sticky at any elevated temperatures, a mold release agent might have been used during the molding/vulcanization process. That chemical might act as a lubricant until it is worn off the tread surface. This is another reason for scrubbing new race tires.

But a race team might decide to skip this process and use unscrubbed tires, called "stickers" because the manufacturer's label is left on the tread when the tires are mounted. These labels wear off and disappear quickly but they're easily seen when the car pulls out on pit lane. The softer, unscrubbed tire might develop more grip for a lap or two and therefore work well for qualifying. But if tire wear or overheating is a potential problem, new tires need to be scrubbed before race use.

Scrubbing recommendations vary so the manufacturer's procedure is obviously the one to use. Generally the best way to scrub in new tires is to put them through one heat cycle, gradually loading them up but avoiding sliding. A couple of laps, minutes if the track is short, will do the trick, building up to a final lap almost as fast as a race lap. To complete the heat cycle the tires can cool naturally sitting still in the paddock. If that's not possible, some slow laps allow cool-

ing. Some people cover scrubbed tires with wet rags to cool them quickly. It's probably better after scrubbing to cool tires unloaded, so either take them off the car or put the car up on jack stands.

Pre-Scrubbing Tires

The number of people using their road cars in some form of racing increases every year. Enthusiast organizations such as Porsche and BMW clubs hold track events that allow their members a way to have fun and work their cars harder than is safe on public roads. Autocross events are popular also. Autocross competitors race against time on a course so compact it can be set up in a large parking lot. The success of the Sports Car Club of America's Spec Miata class is amazing. In the summer of 2002 a race at Laguna Seca in California started 70 cars and was won by a racer who drove his car to the track.

These people racing their road cars want fast, reliable tires, and some tire manufacturers have developed unique competition tires that meet U.S. Department of Transportation (DOT) standards. These tires feature hybrid radial construction (that means cord angles slightly less than 90 degrees) and sophisticated tread compounds. Just like other high-performance parts, these tires will provide more consistent performance and last longer if they are properly scrubbed in.

The Tire Rack is now the largest mail-order tire retailer in the U.S. The main facility in South Bend, Ind. features 500,000 square feet of warehouse space and an evaluation track that allows their salespeople to drive the tires they sell in both wet and dry conditions. The Tire Rack also sells competition tires and they offer a heat-cycling service so their customers don't have to use track time to scrub in tires.

The Tire Rack heat-cycling system, shown in Fig. 8.1, holds a mounted, inflated tire between a set of rollers and an electric motor rotates the tire against those rollers. The force applied by the rollers loads the tire similar to the way it's loaded at the contact patch on a car and the tire increases in temperature in the same way it does when it's driven on a track. Rubber in the tire absorbs energy and heats due to hysteresis. There is no external heating required. The process continues until the tire reaches the correct temperature for that type of tire, and each tire gets a

Fig. 8.1 Heat-Cycling Machine

stamp certifying the process, which takes 12 to 20 minutes and costs $15 per tire.

In developing this process, Tire Rack people measured tread temperatures with a tire pyrometer to confirm that in this controlled environment they were able to achieve appropriate and consistent temperatures across the tread without causing tread wear. They consider this process a significant improvement over heat cycling tires on a track. And the 24- to 48-hour relaxation period necessary for the full benefit of a heat-cycling process happens while the tires are in transit to the customer, so the tires are ready for use as soon as the customer receives them.

Shaving Tires

A slick-treaded race tire generates more grip than a road tire with a grooved tread. Even if the footprint, construction, and tread compounds were identical, a slick tire with a thin tread would produce more grip than a thick-treaded, grooved tire. As explained in an earlier chapter, any road-car tread design prioritizes wear, wet traction, and quiet operation over maximum dry traction. A thick tread with a proper road-car pattern breaks up the contact patch into small, thick tread blocks that distort and squirm under stress, reducing dry performance.

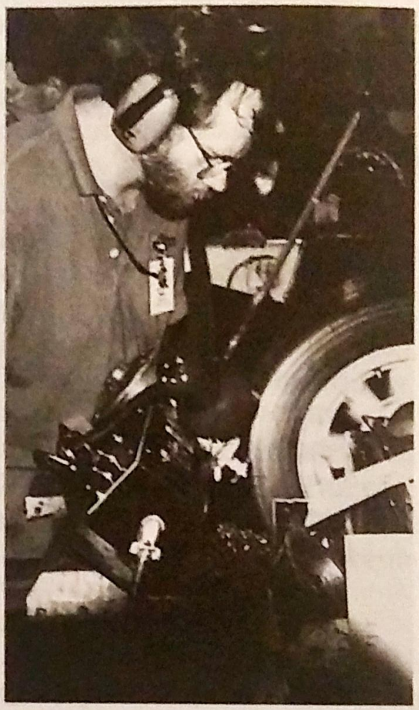

Fig. 8.2 Tire Shaving

A good road tire provides its worst wet traction and best dry performance just before it wears out. But during use tread rubber hardens and looses flexibility, reducing the tire's grip. So a new road tire with most of the tread thickness removed will generate more traction than a tire worn down over time to the same tread depth. That's why racers use shaved street tires when rules prohibit racing tires.

Fig. 8.2 shows a tire-shaving machine removing tread from a new tire. Tire shaving is a great way to get more grip from a street tire. Tire shaving removes tread rubber and reduces tire weight by several pounds. Because of the shape of the sidewall the contact patch is usually wider after shaving, putting more rubber on the road.

Shaving makes a tire more responsive by reducing tread-block squirm. This also reduces heat buildup and lowers the risk that the tire will "go off" or blister due to overheating the tread compound. Because a full-tread-depth tire heats up and wears so badly in race conditions, shaved tires used in competition can actually have a longer useful life than tires that are raced at full tread depth.

Some DOT competition tires, the BF Goodrich g-Force T/A R1 and Hoosier R3S03/A3S03 radials, for example, are molded with only 3/32 in to 4/32 in of tread depth and do not need shaving. Others tires, like the Kumho Ecsta V700 Victoracer, begin with almost 6/32 in of tread depth, so they can be used as is for a wet track or shaved for dry competition. Most ultra-high-performance summer tires begin with 10/32 in of tread depth. The Tire Rack recommends shaving them to about 6/32 in for competition use.

How thick a tread do you want? Racers find that tires stored over a winter loose a lot of grip, so there's no use leaving more tread on a shaved tire than you'd need for one season of racing. And if you have an event that's important enough that you would buy a set of tires just for that weekend, have them shaved down to 3/32 in and you'll get even more grip than 6/32 in would give you.

Tire Temperature and Pressure

Rubber friction is sensitive to temperature, so tires provide maximum grip in a small range of temperature. 180 to 220 degrees F, as measured when the car is stopped immediately after coming off the track, is a general goal for a working temperature. Tread surface temperature during actual use has been measured by infrared sensors at over 300 degrees F. Check with the manufacturer of your tires for the correct operating range of your tires on your car for a particular day at a specific track.

Tire temperature data, gathered correctly and consistently, is priceless. There is no substitute for good data. Tire pyrometers in a wide range of prices are available from racing supply houses. Read the pyrometer directions, ask your tire supplier to recommend a procedure, place the probe into the rubber exactly the same way each and every time, and record the data.

Look at the data. You should have at least three readings across each tire taken as quickly after a hot lap as possible. If the tire is hot on the edges or cold in the middle add some air. If it's hot in the middle, take some air out. Hot on one edge might indicate you have a camber or toe problem.

If you recorded your cold tire pressure you can record the hot pressure when you take the tire temps and compare the two measurements. Pressure gain can give you an idea of how much you're working the tires.

A tire gains internal pressure as it heats up. If possible, always work with an inflation pressure measured when the tire is cold. Know how much pressure build-up you get for each track you run. That way, if you need to change inflation pressure in a tire during a pit stop, you know the proper cold pressure that will result in the right pressure after the tires get up to working temperature. That's when you need max grip.

Think about your tire data and make sure you're making the measurement consistently and recording it accurately. Is one side of the car in the sun and the other side shady? That can affect temperature and pressure readings. Put the palm of your hand on the tread. If you can feel a temperature difference tire-to-tire with the car sitting in the paddock, think about what effect that might have on your hot and cold pressures.

Professional teams inflate tires with dry nitrogen. Moisture in the tire causes more pressure buildup when the tires get hot. Water inside the tire turns to steam and increases inflation pressure. Racers on a budget too small to include dry nitrogen should consider using a dryer with replaceable cartridges on their compressors. The bottom line is that internal pressure is what supports the load on the tire. And the correct inflation pressure maximizes contact-patch area and minimizes contact-patch load variation, allowing your tires to generate more grip.

Taking Tire Temperatures

Tire companies involved in racing provide technical support at racetracks during test sessions and races. Tire engineers roam the pitlane, taking temperatures and advising race teams on tire issues.

At a CART race at Road America I talked to Dwayne Joyner, Firestone project engineer, about tire temperature procedures and technique. "We have a certain way we do it," Dwayne told me. "Why? We just do it that way to be consistent. We take temperatures on all the tires if the car does more than one lap on the track. We want to work each tire from cold to hot so on road courses that's outside shoulder to inside shoulder. They use a lot of negative camber on road courses, so the inside of the tire gets hotter. Camber is different for ovals so we just start on the cool side of the tire. No mattter what type of course we first check the outside-front tire as the car sits on pit lane and then go to theoutside-rear, the inside-rear, and then the inside-front.

"We want to bury the temperature probe past the needle tip. The temperature we get is the average of all the rubber covering the probe, so we want to stick it in there far enough to read down to the cords. We take three readings across the tire to get an idea of how camber is working for that tire. Temperature readings also give an indication of wear. As the tread gets thin it moves less and there's less heat generated."

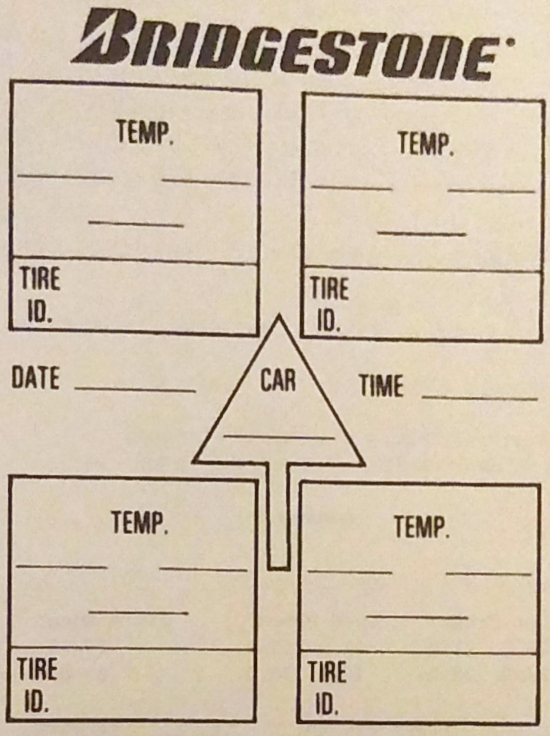

Fig. 8.3 Bridgestone/Firestone Temperature Form

The Firestone engineers take readings and write them on a form that looks like Fig. 8.3. That form comes from a pad that makes a copy for the tire guys to keep and they give the original to the team.

At that same event I talked to Gary Blalock, who supports the Trans-Am teams for B.F. Goodrich, a brand actually owned by Michelin. "We take temperatures on as many cars as we can get to during every session. There's only two of us so we have to hustle. We don't use the normal pyrometers. We use a thermocouple adapter on a hand-held computer, a Palm Pilot. Michelin developed custom software for this system. A printer is built in so we can give a copy to the team right away. Later we can download all the readings from that session into our laptop and keep track of them.

"Our temperature probe is French-made and it's smaller than the probes used by most people. Less mass means it's less of a heat sink and it heats up quickly. We take readings by pushing the probe into the rubber several times and then let it sit still until we see the digital reading just start to fall. We push a button and that reading is recorded along with whatever comments we want to add. The multiple insertions bring the probe up to temperature but also create a small amount of frictional heating, so we wait until it starts to fall off before recording the reading.

"When you're taking temperature readings you have to notice how the tire is contacting the ground, which might not be the same on all four corners. We want to measure temperature at the outside, center, and inside of the actual contact patch. We want the temperature of the tread down near the belts."

Fig. 8.4 shows a print-out from Gary's hand-held device.

BFGoodrich Racing 08/16/02 11:06:03 am

Driver: M. Lewis Car: 12

Session: Practice 1 Weather: Sunny
Ambient Temp.: 73 Track Temp.: 77

Compounds:

Hot Press:		Cold Press:		Difference:	
28.0	27.0	18.0	18.0	10	9
27.0	26.0	18.0	18.0	9	8

Temperatures:						Averages:	
180	190	200	220	200	190	190	203
190	195	200	205	200	200	195	201

Inside - Outside Temp:
20 30
10 5

Comments:

Fig. 8.4 BFG Temperature Form

Michelin has also developed a way for the teams to calibrate their pressure and temperature gauges, making sure they're using the same standards as their tire supplier. Shown in Fig. 8.5, this handy machine has a digital readout for both pressure and temperature. A Schrader valve allows a hook-up to the air pressure source and a heated aluminum block has holes of different sizes to fit temperature probes. If the readings don't match the machine the instruments need an adjustment.

Fig. 8.5 BF Goodrich Calibration Station

Tire Give-Up

A racecar uses a set of tires a length of time, termed a tire stint, mainly determined by the number of laps required to use the fuel allowed by the rules. In most race series it takes more time to refuel the car than it does to change tires, so no time is saved by refueling only. In professional racing there is no reason for the tires to have a useful life that is any longer than a fuel stint.

For most tires the first lap or two are the fastest laps those tires will ever produce. Recently Michelin returned to Formula 1 to compete with Bridgestone in a good old-fashioned tire war. Some Michelin F1 tires appear to increase in performance after five to seven laps and reach peak grip during laps 10-20 before falling off slightly.

The Goodyear tires sold to NASCAR Winston Cup teams these days "give up" at least a second in lap time from the second through the tenth lap and continue to deteriorate until the end of the stint. In fact you can see the tires give up during the two-lap qualifying runs for the Winston Cup races. The first lap is almost always the quickest and

many drivers just run one lap and go back into the paddock. The amount of give-up from the first to the second lap is 0.05 to 0.1 seconds per mile of lap.

So why do tires give up? The reason is similar to that described in the section on tire scrubbing. The rubber in tires, especially tread rubber, undergoes cyclic stress at very high levels. The work done by these rubbers result in heat generation. The combination of high cyclic stress and high temperature is bound to generate mechanical and chemical changes in the rubber.

Some elastomers, and rubber falls into that category, exhibit stress softening and permanent set. Stress softening has been attributed to displacement of polymer network junctions and entanglements and/or the incomplete recovery to original positions of those junctions and entanglements after stress deformation. The presence of fillers introduces possible additional softening mechanisms, including breakage of rubber/filler attachments, disruption of filler structure, or chain slippage at filler surfaces. When intermolecular structures are irreversibly disrupted or reform in new positions while the polymer is extended, the result is permanent deformation. The rubber is said to have "taken a set."

A rubber compound is a mix of many materials, including chemically active agents. An excess of certain kinds of active agents can provide an opportunity for a disrupted or broken bond to repair itself by rebonding at the same location or in a new location.

Another mechanism for tire give-up is more simple. The tire might wear to a tread thickness too thin to generate enough heat and the tire temperature falls out of the range for max grip. A thick tread, even a slick, deforms and the resulting hysteresis generates heat. A thin tread deforms less, generating less heat.

Tire Wars: Goodyear vs. Firestone

Firestone Tire and Rubber Co. and Goodyear Tire & Rubber Co. began their competition in American racing, mainly at the Indy 500, early in this century. Goodyear left racing in 1922 but began a new racing program in 1963, winning the Indy 500 in 1967. Firestone succumbed to the attack and after three straight Goodyear victories at Indy, it retired from big-time racing in 1974. Goodyear went on to build a winning reputation in most of the top racing series in the world, including Formula 1, NASCAR, and CART.

Firestone decided to return to competition in Indy car racing and funded a race team owned by Pat Patrick to test tires privately during the development process. Patrick Racing tested Firestone tires for the entire 1994 race season, logging more than 12,000 miles. In preparation for the coming tire war Goodyear began to rev up its own development

program toward the end of the '94 season. When Goodyear was the only tire supplier to the CART series, development was slow and steady and they brought new tires to a race only after the teams had tested them. But late in the '94 season Goodyear began to bring tires that were made specifically for that weekend and the teams complained about some of the surprises. They weren't used to learning how to adapt their setups to a new tire during a race weekend. Some teams were better at this than others.

The last race of the year at Laguna Seca in 1994 was a good preview of things to come. Goodyear brought tires with a soft, sticky compound and during that race, black balls of rubber could be seen accumulating everywhere around the track. Rubber routinely rolls off a racing tire and accumulates into ropy balls of black stuff that gets picked up again and again on hot tires and thrown all around the racecourse. But this time it was worse than usual. You could see hunks of rubber flying through the air as the cars circulated around the track. The racecars had globs of rubber stuck on their front wings and black smears on the body work where flying rubber had struck the cars.

At Laguna the talk was about "give up." Race tires usually go quicker for the first few laps and then lap times increase as the tires "give up" some performance. Everyone expects it to some degree and it's not all due to the tires. One of the voodoo advantages attributed to the dominant Penske cars that year was the way they seemed to save the tires, have less give up, especially the rears. I was shown some data logged during the Portland race that showed lap times posted by Lola and Reynard chassis increasing more than a half-second between tire changes. Penske built their own chassis back then and their "give up" was less by a couple of tenths. It's tough to beat a car that's just inherently faster by two-tenths of a second a lap!

At Laguna the teams were griping about the tires having a lot of "give up" after about 10 laps. One driver said the difference was more than a second a lap. The tires had grip though and Paul Tracy (driving a Penske) broke the Indy car lap record during qualifying even though the rules didn't allow as much rear wing as they had the previous year.

During the Laguna event I asked one of the Goodyear guys about their tires. John Slikkerveer was at that time field manager for Goodyear's Racing Tire Division. John usually had pretty straightforward answers to my questions. I asked him about the Laguna tire gripes. "It's not a great tire. It gives up after about 10 laps. We tried something and it didn't work."

"Is this mainly something to do with the rubber compound?" I asked.

"That's right," John said. "We learn all the time and we learned what not to do. We'll fix it."

"At Nazareth there was some griping about too much stagger at the rear," I said. (Stagger is the difference between the circumference of the rear tires in inches. On a counter-clockwise oval the right rear tire is bigger so, with no differential in the final drive, the car wants to turn left.)

"That's right," John explained. "We work very closely with the teams, so we get feedback about the tires. They said there wasn't enough stagger at Loudon so we built in more for Nazareth and went too far. At Loudon we had .30 to .31 [inch] and we wanted .35/.36 for Nazareth but we got .40/.41."

This surprised me. "I thought you made a mold and got exactly the size you want."

"We constantly improve our manufacturing process," John said. "But there are tolerances. We're just working with rubber and string here."

I laughed. He said it so matter-of-factly and it was a surprisingly simple description of an amazingly complicated product.

"Are we going to see in CART next year what we've seen in NASCAR?" I asked, alluding to the Hoosier/Goodyear tire war that had resulted in some weird happenings.

"It's been pretty intense with Hoosier this year in NASCAR," John said. "Our goal is to win. We'll never compromise safety but we want to win."

I talked to John again after the race and he said race winner Paul Tracy's tires didn't give up as much as anticipated. "It was only about six-tenths of a second," John said. "And it was a hot day. That's not bad."

Here Comes Firestone

Firestone held a press conference during that same weekend at Laguna and Al Speyer, motorsports department manager, presented some information about Firestone's tire performance during testing. Patrick Racing had used Ford-Cosworth engines limited to 12,500 rpm. They started the year with a '93 Lola chassis and then switched to a '94. This same team planned to run a full CART season in 1995 and Jim McGee would come over from Newman-Haas to become general manager. Trans-Am champion Scott Pruett was to be the driver.

"We're proud of our progress in testing this year," Al said. "We're faster than a lot of the field at every track where we've tested. We expect to finish in the top 10 early in the season. At Indy we ran 224 on a day where the conditions were similar to this year's race day. During the race the best Lola lap was 216. We ran a lot of very comfortable laps under race conditions. I think Jim McGee came back to Patrick Racing because of what he saw. He was up there in the stands when

we were testing. He had his own watch and he could see Scott on the track and he knew what the conditions meant. I think he was impressed."

"I know you want to win races," I said to Al, "but would winning poles at races also be important?"

"I'd like to get the pole at the Indy 500," he said with a big grin.

"I think you have to start the race on the tires you qualify with," I said. "Would it be worth a quick pit stop for tires early in the race to win the pole?"

"It's not that easy," Al said. "You have to bring enough tires for half the field—every different design. It would be good to be on the pole but we'd rather start close up front and then win it with a good, conservative tire. In all our testing at Indy this year we had no loss-of-pressure problems. We blistered some tires but we didn't have any flats."

Firestone Tires Proved Superior

A few races into the '95 season the consensus among the few technical people who would talk to me about tires is the Goodyear tires were grippy when new but deteriorated. They "gave up" a couple of tenths of a second after a few laps, and then lost up to a half-second the next 20 to 30 laps.

"The Goodyears even look slick," one engineer revealed. "They get shiny after a few laps and the rubber is soft and sticky. They can be difficult on oval tracks because the right-front tire seems to dig in all of a sudden and the car spins."

Another engineer described the difference this way. "The Goodyears get soft and sticky. The rubber rolls off the tires and accumulates on the track. The Firestones stay a flat gray color and seem to abrade into a dust. They're more consistent than the Goodyears. They don't go off and the balance [understeer or oversteer] stays the same."

Patrick's team with driver Scott Pruett gave Firestone its first victory in 1995 on the two-mile oval at Michigan International Speedway. After winning two races in '95 Firestone won 10 of 16 in '96, 13 of 17 in '97, and 18 of 19 in '98.

Goodyear gave up on Formula 1 racing in 1998, and assured their CART teams the reassigned F1 resources would return them to a competitive level of performance. But during 1999 Goodyear could muster only one win, at Portland, and the company announced its retirement from CART in October of that year. Bridgestone/Firestone continued as the exclusive tire supplier to CART using the Bridgestone brand name and to the Indy Racing League with the Firestone brand.

Less Give-Up Can Be a Problem

The finish of the 1999 CART race at Motegi, Japan was a thriller. With four laps to go Adrian Fernandez led but did not have enough fuel to finish under power. Greg Moore, who would die tragically later that year at Fontana, pitted for a splash of fuel and looked like a sure winner. But on the restart Greg's right-rear tire blew out and he slid backwards down the straight, causing a yellow flag that allowed Adrian to slow and make it to the end and the victory.

Greg's dad, Ric, told me during the following race at Long Beach, "It was amazing Greg didn't hit anything. Rick Mears came to me and said that was the best save he'd ever seen."

The tire companies don't like to talk about tire failures. Firestone's parent, Bridgestone, is of course a Japanese company, so that failure at Motegi had happened in front of all the Big Guys. The first Firestone guy I asked about it at Long Beach told me to talk to Page Mader, now head of Firestone's race group. When I found Page he shook his head and said, "I can't talk about it."

Later that day when I passed Dale Harrigale in pit lane I said, "Hello," and kept walking. Then I turned back and told Dale, "I just want you to notice I didn't ask you about the tire problem at Motegi." We had a good laugh. All of us were used to me asking questions and them not answering. Sometimes it pissed me off, but on this day I thought it was funny.

Later in the weekend I talked to Firestone's Al Speyer. He was more forthcoming, maybe because he had a positive spin on the story. "We knew we had a marginal tire at Motegi. There was too much wear on the inside shoulder of the right-rear tire. If the teams hadn't stretched out the number of laps on the tires we would have been OK. If the pit lane wasn't so abrasive we'd have been OK. We told the teams not to spin the tires out of a pit stop when the tires were hot and worn.

"The performance of the tires doesn't degrade much over the life of the tire so the teams use them longer. When they want to make up time in the pits they don't change the tires knowing they still have the grip. Greg's tires were used up. We were hoping for an earlier yellow flag so everyone would change tires, but the yellow didn't happen until four laps to go. Greg burned out of his pits and the tires just couldn't take it."

Why Didn't Goodyear Respond with a Competitive Tire?

It's too bad the war ended. Competition between the two companies added a lot of interest to CART and IRL racing. I'd love to see Goodyear return to CART racing.

Why didn't Goodyear just make a tire the same as a Firestone? It's not that simple. A chemical analysis of a rubber compound will tell you what and how much is there but it can't reveal the temperature/pressure/processing history the material experienced during manufacturing. Goodyear would certainly have solved the problem if it had been able!

It seems neither company really knew exactly why their tires were different. And obviously Goodyear had no response, because it couldn't make a tire that had more grip and less give-up.

"It's always been that way," is what people from both companies say off the record. The Goodyear tires have always had more grip when new but deteriorate during use. The Firestones are a little slower during the initial laps but they don't deteriorate as much. The Goodyear tires seem to gain grip by using softer compounds, but their rubber lacks the cohesion and stability of the Firestone material.

Whether it will admit it or not it's my opinion that Bridgestone/Firestone knew it had a way to make better tires than Goodyear before ever committing to CART racing in 1993. It saw the performance deterioration of Goodyear tires during a tire stint as a weakness it could attack and it did that successfully. Evidently Goodyear could not come up with a material or process that could solve its give-up problem. Or maybe the bean-counters wouldn't approve the necessary R&D budget.

During my research for this book I discovered some information that may shed some light on the reason why Firestone tires proved superior to those from Goodyear. My speculation on this is in the section coming up on Abrasion and Graining.

NASCAR—Hoosier/Goodyear Comparisons at Daytona

Quite a bit has been written about the Goodyear/Hoosier "tire war" in NASCAR. In 1988 when Hoosier first challenged Goodyear in NASCAR, the smaller company, located in Lakeville, Ind. just south of South Bend, won some races and definitely shook up the status quo. Goodyear responded in 1989 with a radial-ply race tire that provided better grip, less rolling resistance, and improved resistance to punctures. As explained in an earlier chapter, radial tires are intrinsically better in those areas than bias-ply tires. So, to remain competitive, NASCAR teams had to at least try the new tires.

Hoosier didn't have a manufacturing process for radials at that time and had to withdraw from competition. In '94, armed with new manufacturing capability, it made another run at Goodyear in NASCAR racing. Darrell Waltrip, Harry Gant, and others signed tire deals with Hoosier.

After early-season testing at Daytona I made some phone calls and found out that the Hoosiers were producing slightly lower lap times. Bruce Foss, Hoosier product manager, told me he hated to brag but "It looks like we've got a good tire for Daytona. Teams who have done back-to-back tests say they're cutting two- or three-tenths of a second off their lap times."

Bruce went on to say he didn't really like references to a tire "war." "Things have changed since '88," he explained. "Technology is much better. These are radial tires and they're much more resistant to punctures. The rules have changed too. Back in '88 you could change brand of tires anytime during an event, but now they have to race on the same tires they used to qualify. There won't be all the switching around there was before. Teams will have to think about it and plan it out better. All that's to the good. We're very concerned about safety and I know the Goodyear people are too."

I asked Bruce if these tires are really pure radials?

"When people think of a radial tire, they think about body plies going from bead to bead at 90 degrees to the tread centerline. Modern radial tires, even high-performance street tires, are more of a hybrid construction. The body plies are really at about 83 degrees on street tires and less than that on race tires. [As explained in Chapter 5, the plies in the sidewalls need to be in tension to have enough strength to transmit driving and braking forces between the beads and the tread. A purely radial ply would not be strong enough, but two plies laid at 5 to 20 degrees either side of 90 degrees solve the problem. One ply is in tension in braking and the other is in tension during acceleration.] The compromise is toward low manufacturing cost and long wear for street tires, where for racing we compromise toward grip and low rolling resistance."

Asymmetrical Sidewalls

I asked Bruce about camber. "Are you building some camber into the tires?"

"Yes, we are," Bruce answered. "B. F. Goodrich emphasized that a while back in autocross tires to gave more grip with cars that were prevented by rules from adding camber. That's the situation in NASCAR, where rules and the solid rear axle housing keep the car from having the optimum amount of camber. We're using asymmetrical sidewalls—stiffer inside sidewalls—to generate camber thrust and keep the contact patch in place during cornering."

Asymmetrical sidewall construction and camber thrust were described in Chapter 6.

Heat Cycles

Rubber is a complex substance, a mixture of materials and chemicals manufactured with mechanical processes and various heat and pressure cycles. In use, tread rubber sees mechanical working and time at elevated temperatures very similar to the processes it saw as it was manufactured. It makes sense that more of the same processing would further change the rubber.

The material in a new race tire is semi-stable. If the tread rubber had been totally cured it might be too hard to do its job. So stress and heat can continue the curing process. Even small amounts of energy from ultraviolet wavelengths in sunlight, ozone in air, heat, or mechanical working can cause the rubber in a tire to continue its vulcanization process or change in some way.

The first heat cycle is called scrubbing and was described earlier. Every heat cycle changes a tire to some degree, generally in the direction of harder, less flexible, and less adhesive. Race tires can loose effectiveness before the tread wears through if they go through many heat cycles. For some tires three cycles is too many, while others show a performance drop off initially and then maintain a good level of performance until the tread is worn off. Smart race organizers are incorporating long-lasting tires into their rules so that "spec" tires can lower the cost of racing. Some racers attempt to enhance the performance of used tires with additives and treatments as described later in this chapter.

Abrasion and Graining

The abrasion patterns shown in the photos in Fig. 8.6 were produced by abrading two different rubber samples on different road surfaces. The abrasion profiles compare natural rubber abraded on silicon carbide cloth (the top row of photos) with a worn tire (the bottom row).

What you see here is called graining. The cause, typically, is overly aggressive driving with a tire that is too soft and grippy for the conditions or the driver has overworked the tires before getting them up to a working temperature. Abrasion patterns are not necessarily caused by gross sliding. A requirement for the development of an abrasion pattern is "unidirectional sliding." Sliding in random directions does not produce these patterns. The orientation of the pattern is important because it indicates the direction of relative motion between the tread and the road.

Here's how that pattern gets worked into the rubber. When a new rubber sample is continuously abraded in the same direction, the rubber develops an array of nearly parallel ridges at right angles to the

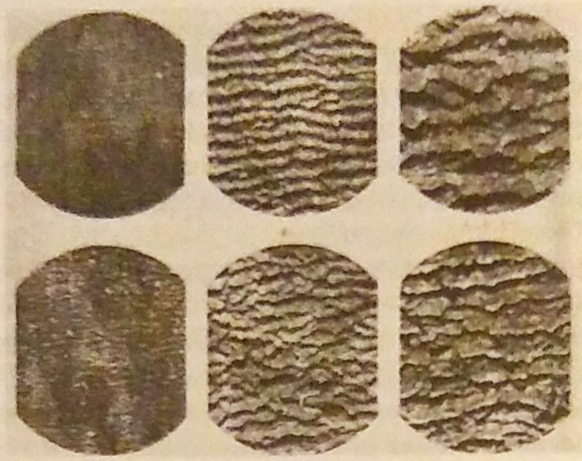

Fig. 8.6 Abrasion Patterns

abrasion direction. The shape of the ridges in cross section, seen in Fig. 8.7, is saw toothed, with the teeth pointed against the direction of abrasion. During sliding, deflection waves in the rubber turn into peaks which are bent over, exposing the upstream side to abrasion. The peaks wear thinner into teeth and the tips are eventually torn off.

Sliding on smooth tracks does not always produce abrasion. Abrasion is generally initiated by local stress concentrations at the contact between track asperities and rubber. Abrasion intensity depends on shape rather than size of the asperities. Experiments have shown that road surfaces exhibit wide variations in abrasion characteristics.

Lab experiments with abrasion in an inert atmosphere—nitrogen—show less abrasion than the same process in air. This leads to speculations that antioxidants in a rubber compound can make it more resistant to abrasion.

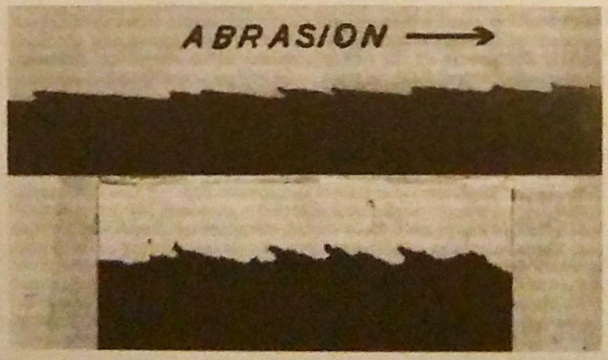

Fig. 8.7 Abrasion Profiles

Unfortunately, once a graining pattern is worn into the surface of a tire it's difficult to wear the pattern away. The ridges tend to perpetuate as wear continues. Even worse, since the tread is not evenly loaded after it has been grained, the tire loses grip. It's just another way for a driver to mess up. That's why experienced drivers are so valuable.

How Firestone Whipped Goodyear

Rubber abrasion is mainly caused by two mechanisms working simultaneously: 1) abrasion due to rubber fracture and 2) mechanical/chemical degradation of the rubber surface. The fracturing mechanism is actually two processes. A loss of "fine-scale" rubber in very small particles removed from the areas between the peaks in the patterns and "larger-scale" particles abraded from the upper sides of the ridges.

The mechanical/chemical degradation is what's interesting. This type of abrasion is caused by large frictional forces on the surface of the rubber. These forces cause rapid elongation of the polymer chains resulting in rupture of some individual chains. When a chain breaks the broken ends produced are chemically active and will reattach somewhere if they get the chance.

What happens next depends on the chemical nature of the compound. Broken chains in natural rubbers and styrene-butadiene rubbers look for a free radical and usually find oxygen, since wear is a tread surface process. A combination with oxygen stabilizes the ends of the broken chains, resulting in a tendency toward shorter chains and a lower molecular weight in the compound, producing a sticky, oily residue. That's what a hot Goodyear tire looked like during the CART tire war.

Other rubbers, polybutadiene for example, join with other chains after breakage, resulting in additional crosslinks. A higher percentage of crosslinks is a tendency toward a higher molecular weight, producing an abraded material that is dry and powdery. That's how the hot Firestone tires looked.

What myself and other people saw during the CART Firestone/Goodyear tire war were tires that looked very different when they were hot. The Goodyears got black and wet looking. They seemed oily and abraded rubber rolled off in greasy hunks. The Firestone tires looked dry and gray. Their debris was dry and powdery.

Years ago I had a conversation with a Firestone engineer who shall remain nameless and the subject of that talk fits into this discussion. I was doing my usual deal of asking different people the same question and comparing the answers to try to piece together some relevant information. The subject was what's going on with tire give-up and I said something like this. "I guess a tire working hard on a racecar

is getting some intense heating and mechanical working. I'd think this would break some of the polymer chains and crosslinks. Is that what causes give up?"

This engineer said something like, "Yes, I think so, but there are things you can put in the compound that encourage the broken chains to reattach and that retards the degradation of the compound." That fits with the process I described above.

The question remains why Goodyear continued to make tires that got hot and greasy instead of gray and dry. Of course I could be wrong about this oily/dry difference, but even so the question remains. Why didn't Goodyear respond?

Either it didn't know how, or it didn't have the money to develop the technology. Goodyear was trying as hard as it could with the materials and processes available. Firestone had its own materials and processes which Goodyear was unable to duplicate. It was obvious at the time that Goodyear had no recourse and had to quit rather than be repeatedly beaten on the track.

There's a lot of misinformation about tires. People say "Hard running forces the oils out of the rubber." I think this oily residue is what they're talking about but I don't think it actually has anything to do with the oils used as extenders in rubber compounds.

Graining on Dirt

When the track is dirt there's no sense in having a very sticky tire because it would just pick up a bunch of dirt and you'd have a dirt-treaded tire instead of a rubber-treaded tire. But high-hysteresis rubber doesn't help much either because there are no road surface irregularities stiff enough to press into the tread rubber. Dirt tracks start each day wet and sticky. During a race or practice session the track dries out and develops a hard groove in the turns.

Tread compounds used on tires built for racing on dirt have to be versatile but are generally softer than pavement compounds. They need to provide grip when the track is wet and also when the track is dry and hard. Dirt tires slide a lot and this produces frictional heating so dirt-tire tread compounds have to resist that heating and hold together at high temperatures.

These photos show you what graining looks like on tires that have been run on dirt. The track is the Springfield Mile, a horse track at the State Fairgrounds in Springfield, Ill. The track has relatively short straights and long turns and sprint car storytellers talk about guys running an entire lap at full throttle. I took these photos in 2001.

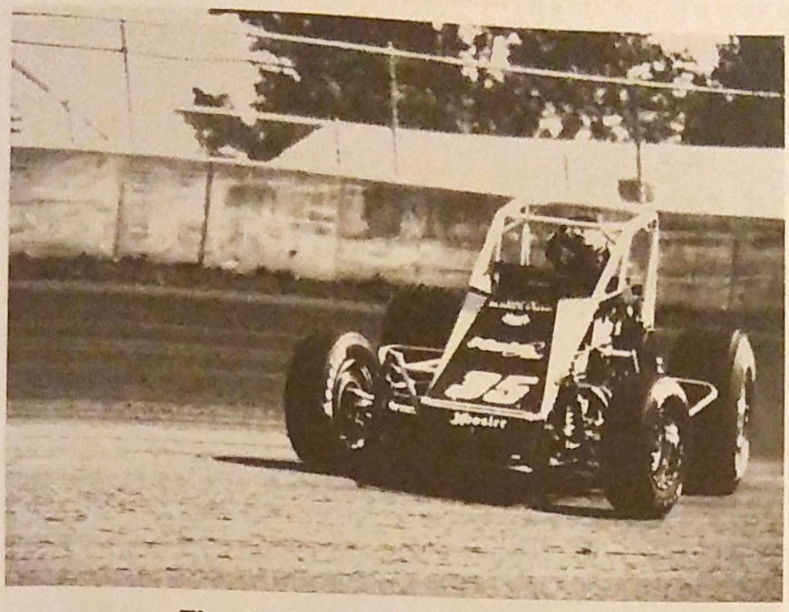

Fig. 8.8 USAC Silver Crown Car

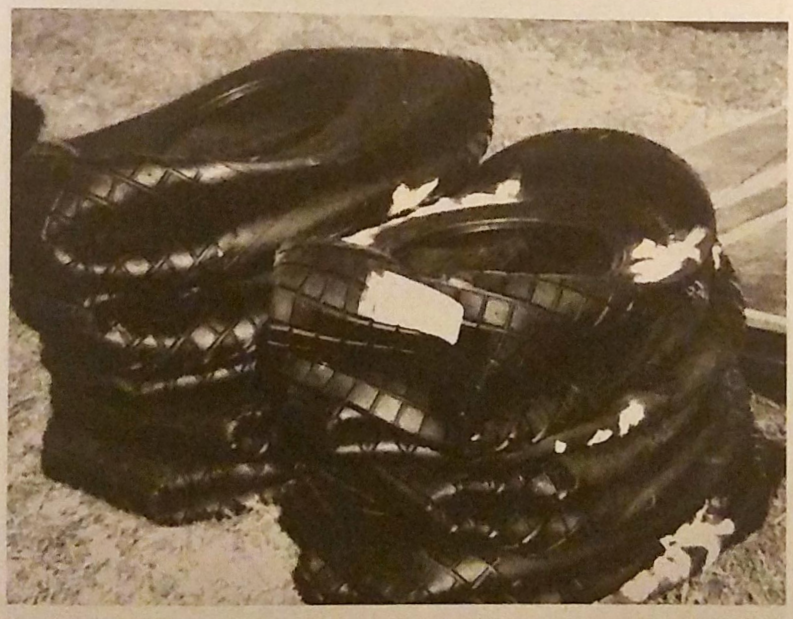

Fig. 8.9 Tires Waiting for Mounting

Fig. 8.8 shows a USAC Silver Crown sprint car hung out in a corner. Some stacks of unmounted tires appear in Fig. 8.9. The tires are compacted for efficient storage. The tread area is obviously not very stiff so internal pressure provides the necessary tread profile.

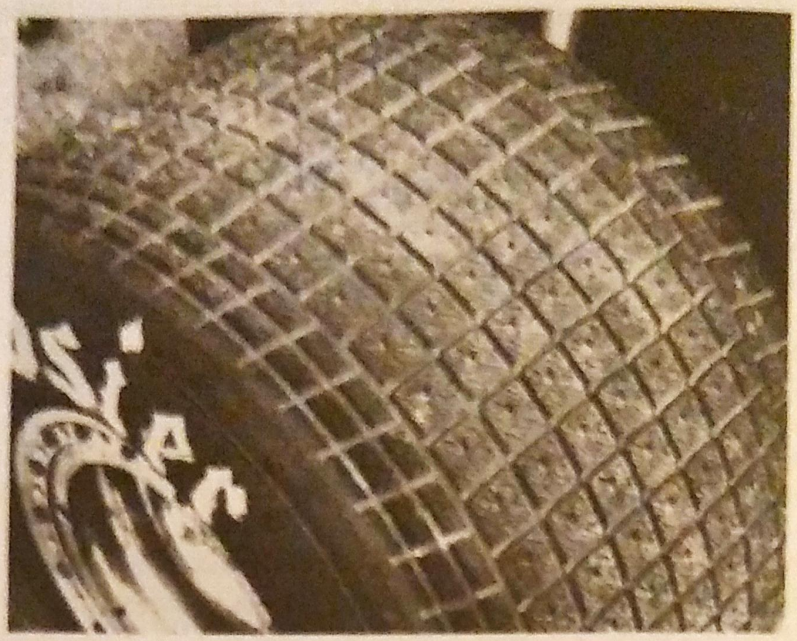

Fig. 8.10 Graining on a Rear Tire

Fig. 8.11 Graining Close-Up

Fig. 8.10 and Fig. 8.11 present detail on graining of a rear tire. The close-up shows the track surface was sliding on the tire up in the direction of the top of the page. If you look back at the photo of the Silver Crown car in a typical power slide coming out of Turn 4 you can see the reason for this abrasion angle, the slip angle. It looks to me like about 45 degrees. The tire sees a combination of driving slip and lateral sliding.

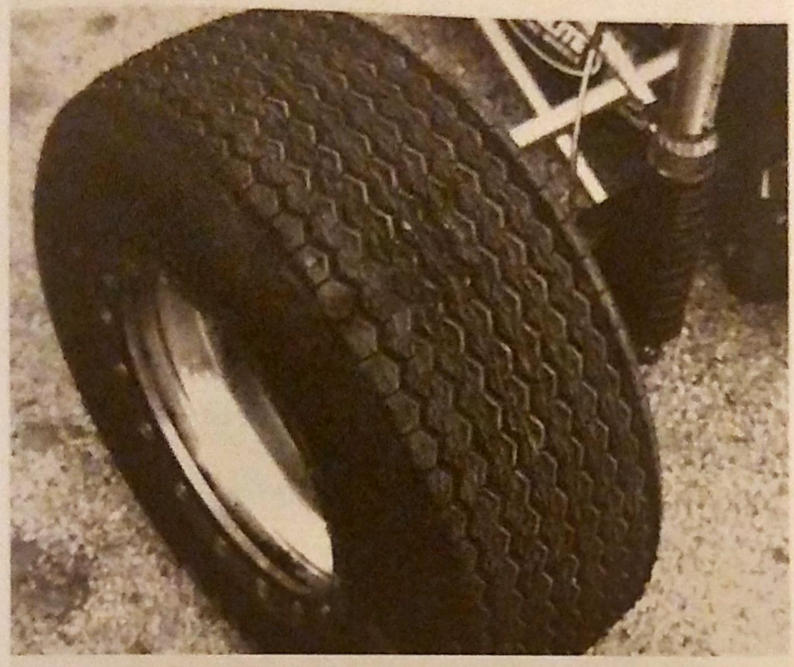

Fig. 8.12 Graining on a Front Tire

The front tire is another story. In Fig. 8.12 the apparent slip angle is almost 90 degrees, meaning the tire was slipping almost exactly across the tread. The rear tires are driven and the forward slip along with lateral sliding produces an apparent 45-degree grain pattern. But the front tires aren't driven, they rotate at the passing speed of the dirt. The front tires only see lateral slip, which produces the circumferential graining shown in the photo.

Figures 8.13 and 8. 14 are a close-up photos of the same tire. The dirt track was sliding across the tire from right to left. The leading edge of each block sees maximum pressure and wore more rapidly. The trailing (left) edge of each tread blocks didn't wear as badly because it could deform into the neighboring groove, lowering the pressure on that part of the tread.

Graining on Pavement

These photos, taken by Ted James, show graining on tires used in club racing on a pavement road course. The tire in Fig. 8.15 shows a front tire with even wear, no graining. The next image, Fig. 8.16 presents a front tire with extreme graining. This tire is toast! The last

Fig. 8.15 Front Tire, the Way It Should Look

Fig. 8.16 Front Tire Graining on Pavement

photo, Fig. 8.17, is a rear tire with graining on the inside edge, perhaps due to excessive camber. The graining is not present across the entire tread, suggesting slippage during acceleration. More camber would create more graining and the pattern would appear over a wider area of the tread.

Fig. 8.17 Rear Tire Graining on Inside Edge

Blistering

In the chapter on compounding we described the vulcanization process and mentioned that if the process goes too far, the rubber can "revert" or return to its uncured state. Reversion can also happen when race tires get way too hot. When you see a driver lock up a tire the smoke tells you something bad is happening. The resulting flat spot is caused by frictional heating of the tread rubber causing reversion. The overheated rubber softens and is scrubbed off the tire.

Another, less severe, form of reversion is blistering. The photo in Fig. 8.18 shows a right-rear tire with a line of blisters around its circum-

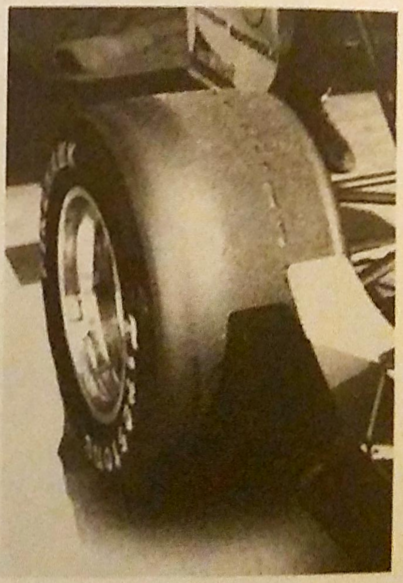

Fig. 8.18 Blistering

ference. Too high cold inflation pressure or too much pressure build-up during use caused the tread to overheat. The heat is generated at the interface between the belt plies and the tread and the rubber melts, causing a local blister.

Mark Blundell won the Fontana CART race in 1997 for the PacWest team but he barely dodged the blister bullet. It was a very fast race on a very hot day. The Firestone guys saw the problem after early pit stops and told the teams to use lower cold pressures that would decrease loading in the middle of the contact patch. But a few teams still had problems.

Some tire companies have developed anti-reversion compounds that resist blistering. That's all I know about it because of course they won't talk about it. And I can see why this would work. If you can run your tire a little bit hotter without blistering that would be more forgiving for the racers using the tire and maybe the tire would give a little more grip at the higher temperature. That's assuming the anti-reversion compound has no negative trade-offs.

Tire Treatments

Most racing organizations forbid tampering with tires, mainly for safety and cost reasons. Racing, however, is extremely complicated and every serious participant constantly bumps up against the rules. So, when any single race team dominates a series, competing teams automatically wonder if they're cheating. Sometimes cheating accusations are made openly, as happened after Jeff Gordon's NASCAR Winston Cup victory in September of 1998 at Loudon, NH. This was Gordon's ninth victory of the year and his fourth in the last five races. Jack Roush, owner of five Winston Cup teams including the team fielding a car for perennial second-place driver Mark Martin, accused Gordon's crew chief, Ray Evernham, of using tire-enhancing chemicals. NASCAR impounded tires from Gordon's race-winning car and those from the car of second-place Martin. NASCAR had the tires tested.

Gordon earned the pole position for the Loudon race, but after the start he was forced into the unforgiving outside groove and fell back to 17th. He had worked his way back into the top ten, but the car did not look like a winner. Meanwhile Mark Martin, driving for Roush Racing, had dominated the race. A yellow flag on lap 233 brought most cars into the pits for fuel and tires. A few teams decided to improve track position by replacing only two tires. Evernham made that call for Gordon's car and he beat Martin out on the track and took over the lead.

Martin found himself yet again chasing the DuPont-sponsored, rainbow-colored number 24. Martin drove his car to the limit lap after lap, even brushing the wall exiting a corner. John Andretti seemed to

have the best car at the end of the race. He improved to third place and chased Martin down but didn't have enough speed to pass. "My car seemed to come to life with those two tires at the end," Gordon said.

The Monday after the race the TV show *RPM 2night* reported Jack Roush said he had received a letter that claimed Gordon's team, Hendrick Motorsports, had bought chemicals marketed to enhance tire performance. Roush claimed Jeff Gordon's lap time decreased by 0.7 seconds after a late-race pit stop when the 24-car took on only two tires.

RPM 2night viewers saw a taped report showing Roush yelling "Get out of here!" at Evernham in the Loudon garage area after the race.

Evernham's reply was, "I'm going. But I'll tell you what we're putting in the tires. It's air, Jack."

Evernham said during a TV interview a few days later that he would like to see that letter and know who wrote it. Evernham was irate and expressed his regret that a cheating accusation would tarnish the accomplishments of the team.

Tire Treatments Are Widely Available

Ted James is a friend and a knowledgeable racer. He and his wife, Nancy, live in Northern California where they build and race competitive racecars. Ted and Nancy started racing with a Lotus 61 Formula Ford in 1974 and have competed almost continually in various classes since. Ted designs, builds, and maintains their cars and Nancy drives them. She currently holds the SCCA D Sports Racing lap record at seven different tracks. I asked Ted about tire treatment products.

"I use Hot Lap," he said. "It's a clear, pinkish liquid that you put inside the tire and paint in coats on the outside. You let it puddle inside the tire and rotate it. It soaks right in. It's expensive stuff, maybe $150 a gallon, but it works. It softens the tire, but not much. The tire comes in quicker when it's cold and has more grip so it doesn't slide as much. You can really lean on them right out of the pits and tire temperatures and pressures stay lower. I don't think they make the car a lot faster but you can use the tires longer. I used to count heat cycles and throw the tires away because they got too hard. Now we use the tires until the cords show and they work just as good the last lap as the first."

Ted also knew about the Roush/Evernham confrontation. "NASCAR won't find anything," he said. "I think it just puts stuff back in the tire that gases off as you use them. An analysis won't find anything that isn't supposed to be there. You can't smell it. Pro-Blend is the company that makes Hot Lap and several other products, including one you can spray into a mounted tire.

"I think this is what happens at a Cup race. Goodyear mounts and inflates the tires with compressed air. Then the teams let that air out and replace it with dry nitrogen so the moisture in the compressed air doesn't add to the pressure when the tire gets hot. If I wanted to use it illegally I'd rig it so the stuff sprayed in there when the bottle was laid down and not when it was standing upright."

Hot Lap, Hot Lap II, and LMT

Ted gave me an 800 number for Pro-Blend Chemical Company in Winston-Salem, N.C. People at the company answered questions over the phone and sent literature. They have 73 unique products for use by hard-core racers, including lubricants and additives for cooling systems, transmissions, and engines.

A person at Pro-Blend knew about the Roush/Evernham face-off and didn't want to be quoted because of the sensitive nature of the controversy. He said their tire treatments are undetectable. The labels on the cans proclaim, "Designed to pass tire tests" and "Undetectable."

Pro-Blend said its tire treatments will lower lap times by a few tenths of a second on both pavement and dirt. The extra grip gives the driver another lane to race in and higher corner speeds. Since the tires are rolling and gripping, tire temperatures are lower and internal pressure won't build up as high. Higher cold tire pressures should be used to ensure correct hot pressures. The racer gets more sessions out of a tire. The car is more drivable and therefore safer. The promoters like it. Fans like it. Drivers like it. Car owners like it.

Well, maybe not Jack Roush!

Hot Lap is the original product. It claims to decrease lap times 2- to 5-tenths and increase tire life up to 50%. The racer uses Hot Lap by wiping the glaze off the tires with gasoline, scuffing with a wire brush, and applying 10 coats to the outside of the tire. A 4-inch roller is recommended, and it takes a few days for the total treatment. They say to apply four coats the first day, waiting 45 minutes between coats. Do the same thing the second day. The third day apply two coats and then wait three days before racing. It recommends applying 10 ounces inside each tire also.

Hot Lap II takes fewer coats and less time before the race. The label says "Super quick for 25 laps."

LMT, which stands for Last Minute Treatment, is quick-acting and can be applied the day of the race. It's meant to be used for qualifying or during the first 25 laps of a race. If the racer can't get the tires until just before the session or the application of such chemicals is not allowed by the sanctioning body, LMT can be blown into the tire during inflation.

When we said we thought the product had a provocative name, the person at Pro-Blend replied, "It's meant to be."

Did Gordon's Car Use a Tire Treatment?

Obviously we don't know the answer to that question. It seemed to me as I watched the race on TV that Jeff Gordon wasn't any quicker after the two-tire stop. He gained track position due to the shorter time in the pits and the adjustments they made improved the handling. A couple of tenths at Loudon is a lot!

Air-pressure changes would have also been necessary, however, if Evernham DID use Hot Lap or one of the other similar products. Because of the better grip and less sliding, the tires would need higher cold pressures to ensure correct pressures after the first few laps.

It seems these tire treatments do work! They aren't voodoo products. They are legal in many racing series, but not in NASCAR Winston Cup. It's improbable that a team in the running for the Winston Cup championship would risk cheating. There is just too much money, too many sponsor relationships, and too many personal and professional reputations at stake. If NASCAR had proved the 24-car did use one of these products, people could face some big penalties.

So why did Jack Roush make the accusation? He was probably provoked by the letter claiming the DuPont team bought some of the material. But buying a product is different from using it in a race.

Roush was enormously frustrated. He owns a quarter-billion dollars worth of high-tech companies and fields five Winston Cup teams. In spite of that the best he could do at that time was finish second behind Gordon's car.

Buoyed by a team wounded by the Loudon accusations, Gordon won his tenth race of the year and sixth out of seven at the next Winston Cup stop at Darlington Raceway, earning a million-dollar bonus. Mark Martin DNFd with an engine problem. NASCAR did not have test results from the tires confiscated at Loudon, so at Darlington they randomly confiscated tires and initiated new procedures that limit a team's opportunity to alter their tires.

After the win ESPN's Bill Weber asked Gordon, "Did your team come here a little mad?"

"Absolutely," came the reply. "We certainly proved something today...We're doing it fair and square...Ray was on a mission."

To this observer it appears that Gordon waits until his car is balanced and his tires are up to pressure and temperature before he makes a move. Other drivers overdrive the setup and they cook the right-rear tire when the car is loose and the right-front when it's understeering. Gordon's feedback about the car and Evernham's experience and smarts worked together to dial in the car for the last part of the race. A smart, patient driver might be the best tire treatment of all.

Tire Companies Do Not Like Tire Treatments

Safety is the major reason given by racing tire manufacturers when they recommend against using tire treatments on their tires. They spend a lot of time and money coming up with rubber compounds that give satisfactory service life without tire failure. They rightly fear any unknown chemical treatment of their tires.

A Tire Guy Speaks Out

Al Speyer's job is executive director of motorsports for Bridgestone-Firestone, Inc., Nashville, Tenn. Al's enthusiasm for racing and persistance fueled Firestone's return to Indy car racing in the mid-90s. His current position is mainly executive in nature, but for 15 years he designed and developed tires for industrial and racing applications.

Al is a racer, and he's one of the people I seek out at races to talk about Motorsports isssues, both technical and political. He and I had engaged in conversations over time about the unique characteristics of tires and the dire situations race teams get into when they make mistakes with the tires. He agreed to talk about these and other topics in an interview for this book.

AS: "Particularly in the racing environment, we fine tune the tires for every individual track and car combination. All of those internal differences, such as the construction and compounds, are things that the individual racer can't do anything about once they get to the track. All they can change are the suspension settings and inflation pressure.

"One of the best ways to describe these differences, if you look at the range of tires we make for open-wheel racing, a street-course tire that we would run on a track like Long Beach or Vancouver wouldn't last more than one or two laps at a high-speed oval like Fontana or Michigan. It would just run too hot. On the opposite side of that, if we tried to run the tires we make for Fontana for continuous lap speeds in the 230 mph range, at Long Beach; all the drivers would be skidding off the track and complaining they have absolutely no grip, because the tires are so hard compared to their normal street-course tires. While the tires look virtually identical outwardly, the internal features make them completely different tires suited only for one application or the other.

"The tires are the only link the car has to the race track. You've got four contact patches where the rubber is actually touching the road, and those patches have to transfer all the acceleration, all the braking, and all the turning that the driver inputs that make the car handle around the corners and brake and accelerate on the straights.

"I don't know, Paul, what more we can say about the internal components because that's all proprietary in nature."

PH: "That's fine, what else would you like to talk about."

AS: "I'd like to talk about what the individual racer can do, whether it's a team engineer or a club racer or an individual driver that's setting up his car. They get delivered a product that we spend endless time and effort making consistent and proper out of the factory. But when that tire gets put into service, the tire probably only accounts for half of its end performance, and the other half is how they treat it.

"Specifically the inflation pressure, the heat cycling, and the suspension settings, and probably most important is the camber, but toe and other settings can come into play as well. I guess the best example that we can give is of a driver complaining on TV that he got a bad set of tires. This just drives us crazy after all the effort we put into making them so consistent.

The most glaring example is on an oval track where we're running stagger. Stagger, as you know, is having a right-rear tire just a few hundredths or tenths of an inch bigger in diameter than the left-rear tire, so the car will naturally want to turn to the left.

"Well, if in the heat of the race, someone on the team makes the mistake of putting the right-rear tire on the left side of the car and the left-rear tire on the right side, that car won't want to turn left at all, and in fact it will want to drive the driver right into the wall, and he'll be screaming on the radio that something is wrong with this set of tires. But there's not anything wrong with that set of tires, they've been placed on the vehicle wrong, and that's what's leading to the ill-handling characteristics of the car."

PH: "I'm surprised to hear that would happen in a professional race team. You're telling me that is a real problem."

AS: "The mis-application of the rear tires is relatively rare today at the highest levels of open-wheel racing, but I can tell you that it happened at least a few times yet in this most recent season—in 2002. Far more often, what will happen is the teams tend to set their tire pressures higher than they need on track, and then they bleed them down just prior to a pit stop. That's how they make their final adjustment. It's easier usually to let the air or nitrogen out than put it in. What happens much more often than the stagger problem is a tire doesn't get bled down to the proper pressure.

"I've had many times when a team's tire guy will come running up to me and say, 'I forgot to bleed the right rear down. It's 4 psi too high. Don't tell anybody. I don't want to lose my job.' We tend to not want to get people in trouble, but it's a situation where the driver is calling in on the radio saying, 'There's something wrong with this set of tires.' And for what he's feeling, he's a hundred per cent right. The tires are

not handling the way his last set did. But it's not the fault of the manufacturer of the tire, it's not a quality-control issue. It's the fact that the inflation pressure hasn't been adjusted properly."

PH: "Are there any other areas of misuse you can tell me about?"

AS: "Well, we're not going to name names, but I can recall an incident at Indianapolis where a car went out for a few laps of practice—not during a race—and the car went down into Turn 1, and the right-rear tire let go. The announcers were saying the tire blew out, and there's something wrong with it. Fortunately, the case I'm remembering was not a severe accident. The driver wasn't hurt, and within 20 minutes the car and all the pieces were brought back into the garage.

"Relatively quickly one of the officials from the league pointed out what had happened. The right-rear wheel was still intact, and that allowed us to analyze the situation. The team wasn't using tire pressure sensors in the wheel, so they had a dummy bolt in the hole where the sensor would mount, but that bolt was loose. Essentially they had set the inflation pressure when they went out, but the air leaked out of the bolt hole, and the tire ran underinflated. Yes, the tire did blow out, but it wasn't the fault of the tire. It was the fact that the inflation pressure had leaked out.

"In that case we could analyze the failure. The guy responsible was fired from the team immediately. He had caused a significant amount of monetary damage to the team, and they didn't want to talk about it any more. Again, in that case we were fortunate to be able to identify the problem quickly. In many other cases the parts and pieces come back so badly damages from the accident, the wheel may be knocked into several pieces at least, and sometimes we don't get all the pieces of the tire back. If that happens, we just can't tell what happened, and that leaves open the question that maybe it was the tire that failed. In some cases we never do get an answer, but we have so many reliable miles behind us with teams that don't make those kinds of mistakes that, when we do have a problem, far more often than being a tire's fault, it's been an application problem."

PH: "For anybody using tires in racing, what are the things they absolutely have to do to make sure that they get the best use out of those tires?"

AS: "The biggest thing is having the proper inflation pressure in the tires, and the second most important thing is working with someone knowledgeable, hopefully a real tire engineer, who can take tire temperatures across the surface of the tread. You need to get more than the surface temperature. You need the internal running temperature of the tire, down between the tread and the carcass of the tire. This lets them adjust their suspension settings, so they're getting the best use out of the slick area of the tire.

"That doesn't mean they'll see the same temperature across the tread. There'll be some temperature differential. Maybe the inside shoulder is 20 degrees hotter than the outside shoulder, but you certainly don't want to have tire running 100 degrees hotter on the inside shoulder and doing all the work there and hardly touching on the outside shoulder, running much cooler there. Then you're only using half of the tire or less and not getting the full benefit."

PH: "What about tire testing, by machine, and track testing? How does that work?"

AS: "The ultimate test is putting the tires on a car and going to a specific track and running them on that track surface. As we talk about, the tread contact area, the contact patch, is important. The other part of that is the track surface. It's very, very difficult, even with today's technological advances, to simulate the track surface on any indoor machine. And the ambient conditions are always changing at the track.

"For handling and the feel of the tire; for whether they have a solid, responsive feel for the driver; or to find out if the construction isn't quite right—they may feel a little twitchy or unbalanced—you still have to go to the track, and run the cars as fast as you possibly can for that car. You not only look at the tire performance, but the driver's comments are important as well.

"Indoor testing, what we do laboratory-wise, is primarily aimed at the structural integrity of the tires—the carcass construction—to make sure that the tires will stand up to high speeds. I can't go into the details of our indoor testing, but I can say that the tires run far more rigorously on the indoor wheels before they ever get to the track. Literally, Paul, they run hours at high speeds—meaning well over 200 mph—before they'll ever get out to an oval track. In actual racing use, our design point might be 100 miles, if a pit-stop window is 60 or 70 miles. We like to look at the tires as hopefully going about one-and-a-half fuel stints. In some cases they'll stretch out as far as two stints. But my point is that the tires will probably never run more than 100 or 200 miles—less than an hour's worth of running. But we stress the carcass on an indoor drum for many, many hours at those speeds to make sure that the tire has the structural integrity to handle the loads.

"We also test at very high ambient temperatures in those laboratories and in some cases a pretty severe combination of the low end of inflation pressure and a high camber setting as well."

PH: "But that's at no slip angle at those speeds?"

AS: "No, we would introduce some slip as well. Slip, camber, high ambient temperature."

PH: "Is that your test equipment, or is that an outside test facility?"

AS: "That's our own test equipment, and the equipment and even the procedure, the process we go through for those tests, is something that we feel is just as important as what goes into the product itself. We don't talk about the specifics of the procedure."

PH: "What about tire data that's given out? Does Firestone give data to anybody other than race teams. Do all teams get that or just some teams?"

AS: "We provide basic data—static spring rate, inflation pressure, weights of the tires—that is made available to all teams that are on our standard lease agreement. In all of our top forms of open-wheel racing, we technically are leasing the tires and controlling return of the tires.

"I'll go off on a sidebar here. I think you know, Paul, we use a bar-coding system on each tire and we make sure tires come back. Some tires go back to Akron for analysis. Many of them go in trailers to a cement kiln where they're incinerated. That serves two purposes. It's the most environmentally proper way to dispose of the tires, and it also makes sure that they don't fall into the hands of our competitors. We're concerned about that, because each and every tire contains all of our technology. That's why it's sometimes hard to put a price on a tire, because it's not just the labor and materials that matter. If someone with the proper knowledge of the tire industry, cuts one of our tires apart and looks at our construction, it's all there for them to see.

"We were talking about tire data. It's a small technicality or maybe not. We only provide the data to teams. We don't provide it to chassis manufacturers or engine manufactures. However, those third parties, not our direct customers which are the race teams, can get that data from the race teams. The teams do have provisions in their lease agreement with us to make that tire data available to a chassis manufacturer or available to an engine manufacturer, if they sign a rather standard confidentiality agreement.

"A step above the basic tire data are some modeling of the dynamic spring rates, slip angles, and tractive force information both longitudinal and lateral. Also, coefficients for modeling the all-around performance of the tire. We make those available to any team who requests the information. Some teams are far more able to use that data in a proper manner than others.

"But that's because of the transient nature of the tire, and because the temperature of the tire greatly affects its traction properties. You hear people talking about cold tires and yes, tires are designed to operate right around 200 degrees F for nominal purposes. When they come out of the pits and the tires are at 90 or 100 degrees—that transition period when the tires, the tread surfaces, are going from 90 degrees to 200, that drastically affects the traction properties of the tire.

"When you try to do the modeling, one thing that is very difficult to simulate even with today's technology is the temperature of the tire. Maybe it's not widely known, but it's pretty obvious once you get involved, a tire isn't working very hard on the straights; and when you start to turn in for a corner the tire temperature starts to go up, and it will eventually reach its maximum temperature somewhere near the later end of the corner. On the next straight the tread cools down again. Modeling that transition of tire temperatures is still one of the challenges that we've got ahead of us as an industry."

PH: "One of the things I've tried to emphasize in this book is the temperature sensitivity of tires."

AS: "And as the temperature goes up the pressure goes up a little bit, and then pressure goes down again as the tire cools. Those transient phenomena are very difficult to model. To get good reliable data on the indoor machines, you want to run at steady-state or normalized conditions, and that doesn't always give you all the transient pieces.

"That's why you hear guys talk, 'this tire comes in much quicker, it's very consistent from the beginning of the run to the end of the run.' And that essentially, Paul, is working on reducing sensitivity to changes in temperature. It's something we've worked very hard on. If you can have a tire that isn't so sensitive to temperature change and still has a high level of grip, it's a benefit to the team and driver."

PH: "A lot of teams are buying or developing their own software simulations that uses tire data they get somewhere, and they spend a lot of time fudging these simulations with track data, trying to come up with something that will help them in some way. What's your feeling about that?"

AS: "Some people have been fairly successful at it, and others have gone down a dead-end street and gotten off track. It's not a perfect science there, by far. There's some luck and intuition still involved in that, Paul. I'm sure it's not crystal clear that you get all the numbers out of the computer, and model the perfect racecar settings. I don't think we're at that stage yet."

PH: "What would you think about someone making the statement, 'There's no way to dynamically test tires except maybe on a fully instrumented CART or F1 car.' If that's true it tells me that the teams have more data about the tires than the tire companies."

AS: "I'd never say 'no way' to that. But there's just too many variables for us to have enough money and time to do that kind of testing. Essentially there are so many people and so many different teams looking at different suspension settings. Basically we've backed into the optimum settings for today's tires. Unless the tires change dramatically, which they won't, we're all making small changes. Every-

body is very close to the optimum settings. I don't think there is any secret, trick suspension setup or fix that's going to provide any significant gain in performance. It's just not there."

PH: "By backed in you mean that the teams working with the tires have come up with setups that work."

AS: "Right, over time and trying many different things."

PH: "So right now somebody spending a lot of money developing their own simulation in CART or IRL is probably wasting time and money. They probably already know all there going to find out about those tires."

AS: "I would think that's true."

PH: "One of the guys I know who's doing that full time agrees with you. Until the tires change significantly, everybody is up to speed."

AS: "Right, and there's an area of suspension settings that work and everybody's evolved to them. Unless the tires change drastically, which they are not going to do, everybody is pretty close to that sweet spot anyway."

PH: "So the people learning the most about tires right now are the guys in Formula 1—Michelin and Bridgestone—who are out there changing things all the time and are working closely with the teams."

AS: "Yes, I think that's right. There's no question, when there's competition between tire companies, especially at the level of F1, you're going to learn an awful lot about the tires. Part of those simulations are to have the right suspension settings when you unload the car and you go out on the first lap on the track. That area is quite active today."

PH: "That's what I hear from people. Also the sims are good for showing setup trade-offs."

AS: "It goes back to one of your earlier questions about what a user can do. There's a temptation sometimes from the standpoint of the team to run a lower inflation pressure than the tire manufacturer would recommend, because you get more grip. The simplest example there is that for 10 or 15 laps you can get more grip, but eventually the tire will overheat and let go. Ten years ago a lot of people in the paddock had the mindset, 'That's the tire company's problem. I should be able to run that tire any way I want.' But the current thinking has changed to, 'When that tire lets go because it's been abused, it really hurts our race team as well.'

"When the tire lets go, it puts the car in the wall, and you don't win the race that way. If you go outside the manufacturer's recommendations, lets face it, the tires can only take so much abuse. They are not immune to being run too low on air. The big enemy of the tire is really heat, and when you don't have enough inflation pressure the tire runs too hot, and eventually either the tread compound overheats and blisters or the internal carcass bonds breakdown between the rubber

and the body plies or the tread plies. Essentially the rubber melts, and the tire will eventually blow out. It will only stand a certain amount of abuse."

PH: "Right, low pressure and too much camber seem to be the two mistakes racers regularly make. In this book I say lower inflation pressure is better and more camber is better but you can't go too far."

AS: "That's exactly right."

PH: "Al, I have one question I can't really figure out an answer for. I've been interested in racing almost all of my life, and I got a mechanical engineering degree because of my interest in racing. I wanted to know how things work. But, up until 1997 when I spent that season with PacWest going to all the CART races and writing that book, I assumed that tires were a fully engineered product just like a computer or a plane or anything else out there. I was amazed to find out just how much about tires is still black art, and what a difficult, dynamic system it is. Why did I not know that earlier?"

AS: "I don't know that I know the answer to that. But I don't think it's an uncommon assumption."

PH: "Well, I think you guys might be able to make more money if people thought your tires were a little bit more complicated. I think that might be one of the reasons why the tire industry is making so little money."

AS: "It's very competitive, that's what keeps the prices down. You might think that racing tires are the ultimate because of the computer modeling, but in fact our passenger-tire technology is probably ahead of where the racing tire is. But it's ahead because of other areas such as wet traction, noise, and wear.

"For instance UNI-T is our attempt to simplify the incredibly-difficult-to-explain technology that is in a tire, whether it's in a race tire or a street tire. The LL carbon we talk about a lot, the long-link carbon, is one of the ingredients that really helps reduce that temperature sensitivity I mentioned. It gives our race tires good grip, consistent grip over a wide range of temperatures and also from new tire to old tire. This is the same technology we use in our street tires."

PH: "Can you say any more about what long-link carbon is?"

AS: "The literature we're sending you talks about a clump of grapes, which is what normal carbon black is. Long-link carbon is putting all the grapes in a long, straight line, so when you put a bunch of lines against each other, they interlock and form a much stronger bond.

"It's very difficult. We struggle to come up with laymen's terms to describe tire technology. What we have is not perfect, but it's what we have today. Let me make this analogy. You talked about computers being as fully designed. Many, many people don't know how a computer works. They know what it does for them. They know Microsoft and Intel Inside. Do you know how that chip works?"

PH: "Yeah, I do."

AS: "Well, many people don't though, right?

PH: "Right."

AS: "The computer companies try to get people to want that Intel Inside. And that's where we are with the UNI-T technology. We want them to want the UNI-T technology. They may or may not understand all of how it works, but it's good for them. Even if we can't explain to every individual customer how it all works."

PH: "I hear you and that is the struggle of marketing technical products. How much do you tell in order to differentiate yourself from the competition? I have a similar problem with this book. How technical do I make it vs. making it a broadly popular book. I guess I'm going to air on the side of the information. I'm not going to worry about watering it down.

"The main thing I'm trying to get across here is the complexity of the product. This interview is a big help and I appreciate it."

AS: "Here's another analogy that you can work in there somewhere. Most everybody understands that you can't run an engine without oil. Well, you can't run a tire without enough inflation pressure. And then camber is probably like rpm, too much can cause a problem. And toe too."

PH: "That great, I'll get that in there."

"The bottom line is it's amazing how something so simple could be found by dumb luck in the sophisticated world of engineering."

—Mario Andretti

CHAPTER 9

TIRE TESTING AND DEVELOPMENT

For the first 70 years of the 20th century tire manufacturers simply tried to steadily improve their product while turning out safe, low-cost, long-wearing tires. They used racing to help them test product-improving materials and processes. Racers used whatever tires were available and tire development proceeded at a moderate pace. Just past mid-century racing grew in popularity and tire manufacturers discovered the promotional value of supplying tires to race winners, especially the winner of the Indy 500.

Competition between tire companies, mainly Goodyear and Firestone in the U.S., rapidly accelerated tire development. Race teams are not all created equal and tire companies had to make sure their tires were on cars that could win races. Tire companies often simply paid teams to use their tires. But racers love winning more than money, and few teams would use tires that prevented them from winning races. The tire companies had similar self interests and wanted their tires on cars that could finish up front. A good driver often ended up being paid to use only one brand of tires, at least until a competing brand offered more money.

Tire Testing

Better tires might help a team win races, but only if the team knows how to set the car up for those tires. So tire companies also paid chosen teams to track-test tires for them. They at least paid for the track and insurance and furnished free tires. This improved tire performance because prototype tires could be tested for lap-time improvements while gaining driver feedback, and the team also learned what type of setup the tires liked. Everyone involved in on-track tire testing showed up at races better prepared for each event.

On-track tire testing needs careful planning and tight control. The stopwatch is the primary measuring device, but changing ambient conditions and driver variations prevent using lap times as an absolute value. For this reason control tires of a known specification are used during tire testing as a benchmark for comparison with new tire performance. A driver runs a few laps at a time and tires are constantly changed between runs. Only the tire engineers know what tires are going on the car and an occasional run on a set of control tires helps validate the test. If the driver produces different lap times and different comments every time he drives on the control tires they need to find another test driver.

Before on-board data acquisition, the only information gained from these tests were lap times, segment times (the time it takes to complete a portion of a full lap), tire pressures and temperatures, and driver comments. When data acquisition became widely available, on-board accelerometers could provide data more closely related to the ultimate grip of the tires. On-board computers in data acquisition systems and engine management systems developed additional memory capacity and race teams added sensors to generate data on almost any component on the car.

It's now common for a team to equip a car with laser ride-height sensors, optical sensors that detect slip angle, strain gauges on suspension links that sense forces, and infrared devices that take instantaneous readings of tire-surface temperatures. The irony of this is that few teams have the manpower to adequately analyze all this data. Much of it is never examined.

How Important Is Tire Testing to a Team?

I traveled the entire CART season with the PacWest team in 1997 and wrote a book, *Inside Racing*, about their year. By mid-summer PacWest had won two races and was getting better gear from suppliers. Ilmor Engineering supplied special qualifying versions of the Mercedes-Benz engine and Firestone invited the team to bring cars and driver Mauricio Gugelmin to Sebring for a tire test.

The team had a disastrous weekend at Mid-Ohio partially, because they missed the Firestone test at that track a few weeks before the race. I knew that Mauricio had tested tires at Sebring and we talked about it during the Mid-Ohio weekend.

"We missed the test here [Mid-Ohio]," he told me. "Firestone brought the front tire that Zanardi liked at the test [Alex Zanardi won that race and the '97 CART championship.] and we didn't have enough practice time to figure out a setup for it."

"So you learn a lot about a tire when you test it," I said.

"That's right," said Mauricio.

"Will you get to use the tires you tested at Sebring?" I asked.

"We were testing street-course tires down there," Mauricio explained. "We might use those tires at Vancouver."

PacWest dominated the Vancouver event, as Mauricio finished both practice sessions in P1 on the time charts and won the race.

The lesson here is that racing tires can vary greatly from event to event, especially when tire manufacturers are competing head-to-head in a race series. The tires they bring to a test can be very different, and some can suit one driver's style better than the others. And the team needs time to find out what the car and driver and tire need to produce the best lap times.

Driver Feedback Helps Develop Tires

Frank Secondari is a tire engineer for Kumho Tire. He's spent more than 20 years working in the development of tires for racing and high-performance road cars. He helped me with some of the explanations for this book and read a couple of drafts. Here's what he'd like to hear from a driver who's testing his tires.

"I want to know four things, mainly," Frank told me. "People use different names for these things but basically I'm interested in information from the driver that tells me about response, precision, balance, and progression.

"Response is pretty simple; it's the time delay from driver input to vehicle output. This is often nearly instantaneous at low slip angles, but can be significant fractions of a second at high slip angles.

"Precision is the ease with which a vehicle tracks a line selected by the driver. If a tire is precise it will stay on line and go where it's steered without any deviation. Interestingly, you don't want perfect precision because some of the force fed back into the steering wheel tells the driver the conditions of the road.

"Progression, also called linearity, reflects proportionality of input to output. If input X yields output Y, then 2X should yield 2Y. Many cars are slow off-center—a small input does virtually nothing—and then a very small additional input causes a significant change in direction. Progression also has to do with the feel of the tire near

breakaway—at high slip angles. Is it linear, or does it break away all at once? At the limit of adhesion small steering increases may produce more cornering power, do nothing, or reduce cornering power and even cause the car to suddenly break away.

"Balance, understeer or oversteer, is simple. Does the car slide more at the front or at the rear? One item often missed when considering balance is the instantaneous state of the vehicle. Is it in a steady-state or transient condition? Transient oversteer can create a quasi-artificial steady-state oversteer, meaning the steady-state oversteer would not have been present if it were not initiated by the transient oversteer.

"In straight-ahead driving we want a small on-center spot without response, otherwise the car would react to every subconscious twitch. This is often called the sneeze factor."

Paul Gentilozzi on Tire Testing

Paul Gentilozzi drives a Jaguar XKR in the Trans-Am series. An intense competitor, he's won three Trans-Am championships driving a variety of cars. I caught up with him at Road America during the summer of 2002. At the end of a media event I asked him if he had time to talk about tire testing. He replied that he did, so I whipped out my tape recorder and we began.

PG: "Tire testing is a privilege and a demon [big grin]. When the tire company chooses your team to test for them it means you get to spend a lot of time in the racecar, which is great when you're young and impetuous. And somebody actually pays you to do it. When you're 52 it's a lot more like work. And the days get longer when you're at Firebird [near Phoenix] and it's 110 degrees.

"I think the interesting thing about it is the first tire test you do on a new development tire. That's always the worst day. The engineers have formulated a tire construction based on the science of the vehicle you're using. Sometimes you go to a tire test and you run 10 constructions and 10 compounds and you come away saying, 'That is really awful.'

"That means that two months later you're going to do it all over again and they're going to come back with different parameters. First they engineer a tire to be durable. If a tire come apart during a race or if the driver gets out and blames the tire during a TV interview, then the marketing advantage of the tire company's participation is completely lost. So always they make a safe tire first. And then they start to make a faster tire, especially in a spec-tire series like Trans-Am.

"Trans-Am had been using bias-ply Goodyears for 15 years and then switched to a B.F. Goodrich radial. They always think they know what you need. We went to the first test and the tire was just awful. We

were counting on it being better than the Goodyears. But we came back a few months later and we got a tire that would live. Then we had a 30-mile tire and it became a hundred-mile tire. But they didn't stop there. They continued the development process in nuances.

"After they get a tire that will last the required pit stop period, a hundred miles or whatever it is, they start to chip away and it gets faster. We're talking two or three tenths of a second at a time. They chip away at compounding and construction until they determine what kind of deflection rates and load rates the tire wants on the racetracks we run at.

"Testing can be arduous and boring. The driver never knows what's on the car. In a typical tire test you go out on track and you do a baseline run on the standard tire. After that you run eight to 10 laps at a time and you never know what tires are on the car.

"When you come in between runs you put the window net down and you give the engineer your opinion. And you don't work on the car for the rest of the day. All you do is change tires."

PH: "So you're not tweaking the setup during this type of test."

PG: "You do that before the test starts. They give you an hour to get a baseline setup on the car. After that they don't give you an opportunity to adapt the car to the tire. They're evaluating only lap times in those eight to 10 runs. And the driver's opinions.

"We'll run 10 constructions in a morning. We'll come back that afternoon and make two or three long runs to test durability. Sometimes the tire that suddenly gave you a half-second improvement is only good for 30 miles. That construction or that compound, it's usually the compound that lets you down, it falls off and you know that won't work. The compounders look at the tires. They look at the graining or the lack of grip and they go back to the lab and find some magic somewhere else.

"It is a big advantage when your team gets selected to test tires, because everybody else then has to tailor their chassis settings to what the guy has who's doing the testing. We see that in Formula 1 right now. The Bridgestone tires are based on what Ferrari wants and the rest of the guys have to run 'em.

"After I've run 10 sets and I've picked two or three tires I like more than the others; they may say this one has an eighth-inch more sidewall material or a little bit different shoulder at the top or a bigger bead. The ability to communicate with the driver really alters how the engineer builds the tire.

"If you tell them the car has a great turn-in and then in mid-corner it loses grip, they'll look at the data and see the lateral force falling off. Then they'll alter the construction to softer initial turn-in and you'll get more grip later. It is really a science, even though sometimes it looks

like mad science. They have a method. I've tested with Goodyear and with Michelin and Goodrich. They all approach it exactly the same way.

"They also evaluate the long run. Say we did three long runs. They'll notice if the car was faster at the end. The cumulative time was better. They'll pick the tire that wasn't necessarily the best at a single lap but was fastest for 60 miles.

"To do those long runs you have to turn off your normal driver brain. You have to say every lap I'm going to stop here, I'm going to accelerate here. The third lap and the last lap have to be within two or three tenths of a second. If you go out and you charge you're going to burn the tires off it and that's not a tire test. That's a chest beating."

PH: "So I assume they don't ask guys to test that can't drive consistent, quick laps."

PG: "They don't want you back if you can't do that. They don't need you to go out there and set a record. That's not what it's about. The idea is to run at a race pace. First of all they have to know that your race pace is representative for where you're racing. You have to be able to run that race pace the entire test.

"If the tire starts to fall off and the driver starts going over the curbs and driving harder to make the lap times better, you haven't accomplished anything.

"The other thing that's vital is that you absolutely have to have a car that runs all day every day. If you go to a tire test and the car breaks, they've got 50,000 bucks worth of engineers standing around. They're not going to invite you back.

"We don't make any money doing tire tests but we don't lose any money. It's not a profit center from a race team's standpoint. It's an enhancement to what you do.

PH: "Anything else?"

PG: "I think that's it."

PH: "Thanks; that was great."

Mario Andretti: Tire Development History

During that same CART/Trans-Am race weekend at Road America I also talked to Mario Andretti. I knew he had been active in tire testing during his driving career so I asked him if he could take some time for an interview on the subject. His answer was enthusiastically positive and our talk was surprising and very interesting.

Mario: "I had the opportunity to be part of the development of really what we'd call the modern-era racing tire. In 1964 when I joined the Dean Van Lines team, it was one of the top three teams in USAC. These were the teams that were doing most of the tire testing with Firestone. That was just the time when Goodyear came in.

Fig. 9.1 The Author and Mario Andretti
Photo by Art Flores

"The tire war at that point was really healthy because it brought a lot of energy to the racing. Up to that point it was totally engine technology in car design. There's nothing like motor racing to give you the forum to just go for it.

"The '60's were just dinosaur technology as far as tires were concerned. For me I looked at tire testing as an incredible opportunity, not only to learn about tires but also getting seat time, learning what makes the difference in the setup of the car, all that.

"I wanted to be involved in every facet of the development. If you look at what happened from '64 to about '74, that's probably the biggest tire evolution until the late '70s when radials started up.

"In '64 we went through the whole development process with construction and compounds and tread designs. I learned all about it. And there were some events that were quite interesting.

"You would think that sophisticated engineering would reason that, on a dry surface, everywhere you have a tire groove there's no rubber so you're losing contact patch. And let me tell you, in the minor leagues, in midgets and sprints on all the paved ovals, we were using slicks. But in the elite racing series they didn't believe in that. They thought the tread design and different designs would make the car behave better yet. But actually the less the design the better it was. They didn't know that the squiggles in the design really don't mean much on a dry surface. They do in the wet.

"In that period I was testing tires for Firestone. Sometimes we'd test right up to Christmas, at Indianapolis believe it or not, weather permitting. So this was December and it was just about freezing temperatures. The test were somewhat tentative but they were in a rush to introduce some new constructions. And one of the tests was going long. The tread on all of the tires were hand cut right before they went on the car."

PH: "So they built them with a slick tread?"

MA: "And then they were hand-cut by the engineers. They had a design pattern to guide them. There was one particular set of new construction they didn't get a chance to cut the tread into but they wanted to run 'em. We were right at the end of the test on a Friday.

"I remember the chief Firestone engineer, Harry Davis, said, 'Mario, we can't groove these tires so go out there and be careful. [Mario smiles, I laugh.] Really be careful.'

"I went out there and set a brand-new track record. In just two laps. And then they called me in, they were very concerned. I said, 'Man, those tires, they really felt good.'

"And they said, 'Wait until we groove them!' [We both laugh.] That was really incredible. It seemed obvious to me the slicks should be better. I'd look at those grooves and say, 'Hey, that's air there, that's not rubber.'

"We didn't really get a chance to try slicks again until they chose that particular construction and compound and they grooved them for the following year. I was struggling like crazy to get to the speeds that I did in three laps on the slicks. They were blaming everything but the real thing. We were blaming the weather, and everything we could think of.

"The bottom line is, it's amazing how something so simple could be found by dumb luck in the sophisticated world of engineering.

"And stagger was the same thing. I found that too, for champ car racing. We were testing at Hanford, Calif. near Fresno. It was a mile-and-a-half track. We ran two races there before it folded. It was promoted by J. C. Agajanian. It was a paved track, a tri-oval, a mile oval expanded to a mile and a half.

"The first corner was part of the original track so it was a tight corner. I was doing some testing there with a very weird-design tire they were trying to develop. It was a wide-tread tire with a narrow rim. The tire didn't compare well with the control tires. But they told me to keep running it.

"All of a sudden I was running a set of tires that loosened up the car, but it was really quick through the tightest corner. Actually the car felt like shit, but my times were competitive to the control tires. I used to be very finicky about the steering wheel position. For various reasons I liked to know the steering wheel was square when the car was pointed straight. If you've got a tire going down or anything like that, getting bumped or if you hit something, it would change the straight-ahead position and I would know it.

"Well, I'm going down the straight on these tires and I noticed I was steering to the right. I came in and said, 'Let's measure the rear tires.' The did that and the right rear was about three-quarters of an

inch longer [circumference], which is about two-tenths [difference in diameter] if you measure it with a tree tape [a tape that converts circumference to diameter].

"I told them to get me a set of control tires and give me that same stagger. I went out and went two seconds faster."

PH: "Those were bias-ply tires. Right? You could get some stagger by putting more air in the right rear and stretching it."

MA: "Yeah, you could over-pressure them and put them in the sun, all of that. We got the stagger and I went two seconds quicker.

"So obviously I had to change the setup to compensate. I had to put more cross weight in the car because the stagger would loosen the car up automatically. I had time to really work on it.

"You know, when you're testing, you have to be very honest and hold nothing for yourself. We had that understanding. But I told Harry Davis, 'This is mine, for one race.' This was '69. [I laugh, Mario grins.]"

"Harry said, 'What do you mean?'

"I said, 'The stagger—the discovery is my thing. It's not to be communicated. I need one race.'

"He said, 'You got it.'

"I was driving that year for the first time with Andy Granatelli. Andy had never won a race ever, with all of his efforts. Not in champ car. I felt I really needed to win a race for Andy. My competition was Al Unser in the new Lola, a superior car to our Brawner Hawk—no question. I put the car on pole by half a second over Al."

PH: "What track?"

MA: "Hanford, the same track we tested at. This was three or four weeks later, in 1969. We went there and I had the stagger thing. I was on pole and there was a big accident. I led seven or eight laps and I was pulling out half a second a lap and I think Ongais [Danny] had a huge accident. They red-flagged the race.

"When we were lined up for the restart I remember seeing Parnelli Jones—he owned the car that Al was driving and he was a Firestone dealer and all. He's scratching his head and checking the tires. [Mario makes a movement of pushing his thumbnail into a tire. You can tell whether the rubber is soft or hard, and if your nailprint doesn't recover, you know it's high-hysteresis rubber.] I was watching all this and thinking, 'All you need is a measuring tape, Parnelli.' He was totally puzzled. It never dawned on him how I could be that much quicker than Al in that car.

"That was the introduction of stagger in champ car racing. These were huge finds when development was usually small increments of gains. Interesting stuff.

"Here again, was stagger something brand new? No. Midget racing. Small inside wheel, big right tire. But they said, 'No, not on the big tracks. Never. That's where they had the engineers.

"I started playing with stagger in road racing. That worked for me unbelievably. In Europe in Formula 1 they had no idea why I was measuring the tires. I knew what I was doing."

PH: "Did Chapman [Colin, founder of Team Lotus and Lotus Cars] catch on to that?"

MA: "I had to let him in on it. He loved that. The other guys, they knew about stagger but they didn't know what to do with it. Most of the tracks over there run clockwise so the predominant corners are to the right. So you put on a bigger left rear.

"But it's not the simplest thing. You've got to compensate with weight, otherwise the car will be so terribly loose. And it would have such incredible understeer on the left-hand corners that it doesn't work. You had to play with the chassis to make it work. You could afford to throw away a little bit of the left-hand corners with a smaller right rear but you still had to negotiate those corners.

"I had 'em really buffaloed for a while."

PH: "Did it help you getting into the corners or coming out?"

MA: "Both. It really helps."

PH: "What kind of differentials were they running in F1 then?"

MA: "You had cam-and-pawl, different kinds of diffs. Limited-slip types. But stagger still works, believe it or not. It's not as effective as with a locker diff. That's what a lot of these guys didn't realize."

PH: "Even with an open diff it would make a difference?"

MA: "It would make a difference. Even if we idle through the corners, there are still ways of making stagger work. Believe it or not."

PH: "What about the switch to radials? When did you first drive a radial tire?"

MA: "I first tested radials about 1974, I think. I ended up in the hospital after a crash during a test at Ontario. A tread separated.

"My next big test was for Goodyear, in South Africa. After '75 Firestone left racing. I didn't think that Goodyear would give me much testing but Leo Mehl [worldwide director of racing for Goodyear] was fantastic. I have a lot of gratitude for how he brought me into the fold. I had been with Firestone my whole career. He treated me like a long-time friend and I became one of their key testers. I developed a great relationship with them.

"It took them a long time to develop the radials. There was so much flexing; I would have to turn way before the corner because the tires were flexing so badly. They had a lot to learn."

PH: "So that was a pure radial, a 90-degree tread angle?"

MA: "Right. I figured the negatives we got to work on. But the positives, they were there over the cross-ply tires. We learned we needed quite a bit of negative camber to compensate for the flexing. We had to learn tons of things, but you could always see the positives.

"But the one thing that radials negated was my being able to play with stagger on the road courses. But I'd still measure the radial tires. If I could get half a tenth, anything at all. I'd always save qualifiers that I found some stagger in. It wasn't much but the only plus side out of that was you could depend on equal tires. Where, with cross-plies, especially with the big tires, you had to measure them or you were in a heap of trouble. You'd put on a set of tires and the driver would come back and say, 'Shit, what happened to the racetrack, what happened to the car?' A lot of guys didn't know. Radials eliminated all of that. It brought conformity back to sizes. That was a big plus. But guys that understood how to play with stagger lost a tool."

PH: "One of the benefits of radials is they generate more lateral force at smaller slip angles than bias-ply tires. Could you feel that?"

MA: "Yeah, immediately. We'd do back-to-back testing and that's one of the plusses you could feel. I could tell that once we got it right, radials would be the way to go. I could tell that radials would definitely beat a cross-ply tire."

PH: "And a smaller slip angle means less induced drag. You could feel that too?"

MA: "It felt like it freed the car up. With the cross-ply tire you had to run a lot more toe-in. Radials didn't like that. So you freed the car up even in that respect. [Less toe-in produces less drag.] In the rear especially. There were sizable advantages you could see right away."

PH: "It must have been a tremendous advantage doing the testing and find out how to use those new tires before everybody else did."

MA: "Yeah, it was. Then I understood the level of camber you had to go to. You don't have to do that today. They've developed the tire to overcome quite a bit of that. But you still have more camber than we used to run with cross-plies.

"Then we got on the ovals and started with two-and-a-half degrees on the right front. We said, 'Put more.'

"'A quarter of a degree?' they said.

"'No, put a half a degree.' And we did another half and another. And we were up to three and a half.

"I said, 'More. Four and a half.' You know it started opening up their minds. We were in totally uncharted waters. And then that became the norm. All those things. Interesting times."

Interesting Times Indeed!

This interview shows that Mario Andretti's driving skills weren't the only reason for his highly successful racing career. I'd say his clever technical observations and intelligent attention to detail helped him a great deal.

Perhaps it's easy to be critical of the tire engineers of those days that the discovery of slicks and stagger for use in "big car" racing happened by accident, and then only at the insistence of a test driver with no technical education. But I think there are some good reasons why it was difficult for the tire engineers to make the transition from treaded tires to slicks.

The unsupported tread blocks in a voided tread pattern allow much more deflection in the rubber than does a slick tread where the continuous rubber is self-supporting. So a soft, high-hysteresis compound would have quickly overheated in a treaded tire. And the exposed edges of the tread blocks would have worn badly. Since there are voids in a tread pattern, the unit-area loading of the tread rubber is higher than a slick of the same contact-patch dimensions which also punishes a softer compound. So anytime the tire engineers would try a softer, higher hysteresis compound, it would blister and/or wear excessively. That type of compound just wasn't in their repertoire. It didn't work!

If, using a typical compound of the day, they had just not grooved the tires, the rubber would have been too stiff to heat up into an acceptable temperature range. The real accident on that day Mario described was probably that the tread compound on the tires they didn't groove was soft enough and had enough hysteresis that, without a tread pattern, it got hot enough to generate good grip.

Once again I have to make the statement, as much for myself as for the reader, that the pneumatic tire is made up of components that interact among themselves with intensity and complexity. A change that seems small might have a result that vaults the product right out of the envelope of acceptable performance. Tire engineers are careful and conservative, and rightly so.

2002 Formula 1 Tire War

By the USGP, 16th of 17 Formula 1 races in 2002, Michael Schumacher had already clinched the driver championship and given Ferrari seven one-two finishes with teammate Rubens Barrichello. Ferrari continued its domination at Indianapolis and also two weeks later at the year's last race in Japan, bumping its one-two finish record up to nine for the year. Ferrari won the constructor's championship with an all-time record of 221 points, equal to the combined total of all the other teams.

After his 64th career Formula 1 victory at Suzuka, Japan, Michael Schumacher summed up the season, "I don't think it is necessary to say more; the results speak for themselves. We have finished all the races, and not only that, but all on the podium, and that shows the quality of the work the mechanics have done."

Fig. 9.2 USGP Bridgestone Front Tire

What the Ferrari mechanics and engineers accomplished pales, in my estimation, when compared to the work done by Bridgestone in dominating its F1 tire-war rival Michelin. While at the 2002 USGP I wanted to get an interview with one of the technical people at Bridgestone or Michelin. Friday morning in the media center I saw an announcement of a "Tire Talk" session with a Bridgestone technical guy. The name at the bottom of the posting was Sarah French, F1 press officer for Bridgestone.

I found Ms. French in the Bridgestone office in Gasoline Alley and asked her if I could talk to someone technical. At first she suggested I talk to the technical manager, Hisao Suganuma, but after hearing some of my questions she thought it better that I talk to the development manager. After some phone message exchanges she arranged a 3 p.m. meeting for me with Hirohide Hamashima, general manager of the motorsport tire development department.

When, at the appointed time, I returned to the Bridgestone office in Gasoline Alley, Ms. French wasn't there yet so I watched the tire busters at work. The garage doors were up and anyone could walk by and watch them. This was in contrast to the Michelin garage, where the busters worked behind closed doors. I wonder what could be learned by just looking at an unmounted Michelin tire.

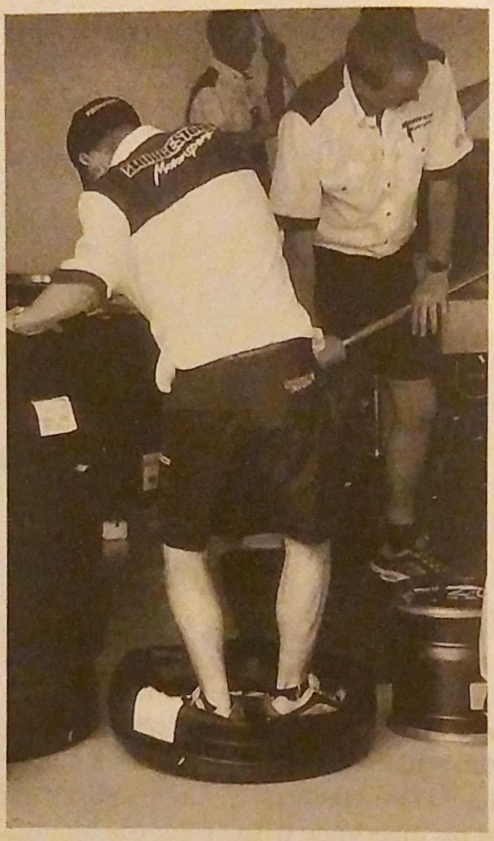

Fig. 9.3 Tire Busters Stomp Tires Down for Storage

Here the guys were demounting sticker tires and stomping them into a jar-lid shape for storage. They wouldn't be able to do this if the "hinge," the point where the tread and sidewall meet, wasn't extremely flexible. This hinge allows lateral sidewall deflection but leaves the tread in contact with the road surface. The hinge also has to be strong enough to pass driving and braking stresses from the tread area to the sidewall plies.

Ms. French arrived just after 3 o'clock and found Mr. Hamashima, an intense, stocky, Japanese man. I'd say his age to be somewhere between 35 and 45. We sat down at a conference table and I explained a few of the topics in my book and then asked if I could record our

conversation. He nodded and said yes. Although I was apprehensive about the noise coming from the tire busters and their machines just a dozen feet away from us, I started the minirecorder and began with a question about F1:

PH: "In Formula 1 you're required to use a 13-inch wheel. What are the problems that creates?"

HH: "13 inches itself is not a big problem. Our competitor makes the same size tires. If we make the wheel bigger, a 15-inch or 16-inch, maybe the tire performance is too much for a human being. At the moment I believe that a 13-inch wheel with this diameter tire is suitable for Formula 1."

PH: "That's interesting. Since the teams have gone to very little suspension movement and they can't damp your tire, are you building damping into your tire?"

HH: "When the tire is working, of course, in traction, braking, cornering, they also work in damping the suspension as well."

PH: "How much of a damping factor can you design into the tire?"

HH: "The damping is working very little because the car is very stiff and they don't want the tire moving so much."

PH: "Right; they want the contact patch to be very stable and predictable."

HH: "Yes, that's right."

PH: "Is there enough damping going on that it could cause a heat problem in the tire? Not hysteresis heating in the rubber, but damping in the tire?"

HH: "At this point no problem. Because a racing tire sidewall is very thin, damping is not possible."

[He had probably misunderstood my question but that final statement is interesting. In order to build some damping into the tire itself there would have to be some extra material in the sidewalls that would deflect and absorb some energy. The earlier statement about the car being stiff and the car designers not wanting the contact patch moving around is also telling. Maybe that's an important tire-design trade-off, flexibility vs. stiffness.]

PH: "I see your guys demounting sticker tires from wheels and I see them stomp them down into a shape for storage. So the place where the tread and sidewall come together must be very, very flexible."

HH: "Ah, yes, that's right."

PH: "And yet it has to transmit a lot of stress from sidewall to tread. That must be a critical part of the design."

HH: "Yes, we have to keep some flex in there. If we don't flex there we will have a problem."

PH: "What cord materials are you using?"

HH: "Ha, ha, very sorry." He smiled, indicating he couldn't tell me that.

PH: "It's not just Kevlar or something that is easily bought?"

HH: "Uuhhhhh; maybe some possibility."

[So they're using Kevlar, probably. It's an extremely strong, high-modulus cord material.]

PH: "What about the bead material? Is it steel?"

HH: "Yes; if we would like a lighter tire then we have a possibility to use Kevlar. And also carbon fiber."

PH: "I assume the bead is not a cable that is butt-spliced. It's a wire that is wrapped?"

HH: "Sometimes. We use many types of beads in our constructions."

[I don't think he understood the question. Road tires used to have beads made from steel wire woven into a cable that was butt-spliced and welded. But this created a fat spot in the bead that caused problems. More often now the bead is made from steel wire wrapped continuously into a circular hoop with a round cross-section.]

PH: "I assume there is some cord angle, the cords are not at 90 degrees to the tread. The tires are not purely radial."

HH: "No."

PH: "But there are belts in the tread."

HH: "Yes."

PH: "And there would have to be two plies in the sidewalls to transmit braking and driving forces."

HH: "Yes, because if we used a 90-degree construction, a pure radial, in that case the capability of control in the corner is very difficult. So a little bit of angle help the driver to easily control the car."

PH: "In a pure radial, the force curve goes up and falls off sharply."[I made a motion with my finger and drew a force curve in the air that went up and fell off quickly after the peak.]

HH: "Yes, right, the force curve."

PH: "It seems like one of the things you'd like to have that is difficult is to have the force and moment peak pretty close together. Is that possible?

HH: "Um, yes, that is a point to develop the tires to have the force and moment circle as big as we can. [He struggled for the right words and then drew a circle on a piece of paper and drew arrows out to a bigger diameter.]

"So we would like to make it as much as possible this way. So this is the target." [He pointed to the arrows, expanding his traction circle. Once again he misunderstood the question but I didn't see any benefit in trying to clarify it.]

PH: "While still maintain good control characteristics?"

HH: "Yes, that's right."

PH: "So the driver feedback must be important during testing."

HH: "Yes."

PH: "And I can probably guess your best test driver. It's got to be ...."

HH: [He finished my sentence for me.] "Yes, Michael Schumacher."

PH: "Was that a tire failure on Barrichello's car today?" [More detail on this later.]

HH: "At the moment we are investigating the trouble. At the moment we can say the fact is the tire pressure suddenly went down but we can't say if it was a tire failure or wheel trouble or suspension trouble; we can't say at the moment. Because of the crash the parts are all in small pieces."

PH: "It's amazing to me seeing how much work the tire does how few failures actually occur."

HH: "If this is a tire failure then we would be seeing more tire failures."

PH: "Is this a handmade tire like most racing tires? Are people building up the tires instead of machines?"

HH: "Yes."

PH: "These assembly people are the elite, or is it just like any tire assembly?"

HH: "It is a special production line. Specific people build the tires for Formula 1."

PH: "I'll ask some more questions about materials and see if you can tell me." I grinned.

HH: He smiled, "Ha, ha."

PH: "What about materials? [He smiled and laughed] See if you can tell me. What about filler systems? I assume there must be some carbon black, but there may be other things. Silica, for instance?"

HH: "Ahh, no."

PH: "All carbon black?"

HH: "Yes."

PH: "But there are many different kinds of carbon black."

HH: "Yes."

PH: "Those are ingredients that you buy?"

HH: "We buy normal production ones but we can buy special ones from the manufacturer."

PH: "And that's the same with all the polymers and all ingredients—you can have things made to your own specifications?"

HH: "The polymer, carbon, and many ingredients."

PH: "One of the things I came across in my research was a description of wear, intense working of the rubber surface. The author made the statement that for some rubber systems, when the polymer chains break they tend to reattach and this makes for longer polymer chains and a higher molecular weight overall. He said the residue of that was a black, oily residue. I've heard tire guys talk about 'the oil

coming out of the rubber.' But this author said other rubber systems tend to not reattach and then the trend is toward a lower molecular weight and the residue is a dry, gray powder. That's exactly what I saw when Firestone and Goodyear were racing against each other in CART in the U.S. A hot Goodyear was a black, oily mess but your tires weren't. [He chuckles] They were a flat gray..."

HH: "Color." [Once again he finished my sentence.] Mmmmm, I don't know the Goodyear materials or what makes the color difference. It may be coming from the oil and carbon. That could be different. But basically racing-car tire polymer is a very, very high molecular weight."

PH: "The molecular weight is high to start with?"

HH: "Yeah."

PH: "It seems to me like the high-molecular weight polymers have more hysteresis. Is that right?"

HH: "Yes, right."

PH: "Rubber makes friction in two main ways: adhesion, stickiness, and hysteresis, deformation friction."

HH: "Yeah."

PH: "Do you continually try to make both of those higher to get better tires?"

HH: "Yeah. We try to make both of those higher but we have to analyze those two characteristics and see which is more important for a particular track, and we decide accordingly."

PH: "Do you go as far as examining the texture of a track to look at the frequency of the deformation that the tire would see?"

HH: "Now we are studying that because the WFL formula is very important for the tire."

PH: "What is?"

HH: "The WFL formula is very important."

PH: "That's the transform ...?"

HH: "Yeah, the frequency and the temperature."

PH: "I remember reading that the lower the glass transition temperature the more hysteresis at a higher operating temperature. The bigger the spread between Tg and the operating temperature, the more hysteresis in the rubber. Is that right?"

HH: "Yeah, it's really important."

[I don't think we were communicating well during this exchange. I mentioned the glass transition temperature in the chapter on rubber friction. I explain what I know about the WLF transform later in this chapter.]

PH: "You mentioned weight. The pressure in the contact patch is higher at the front. The tread rubber is changing direction and decelerating there and there is some momentum transfer creating more force

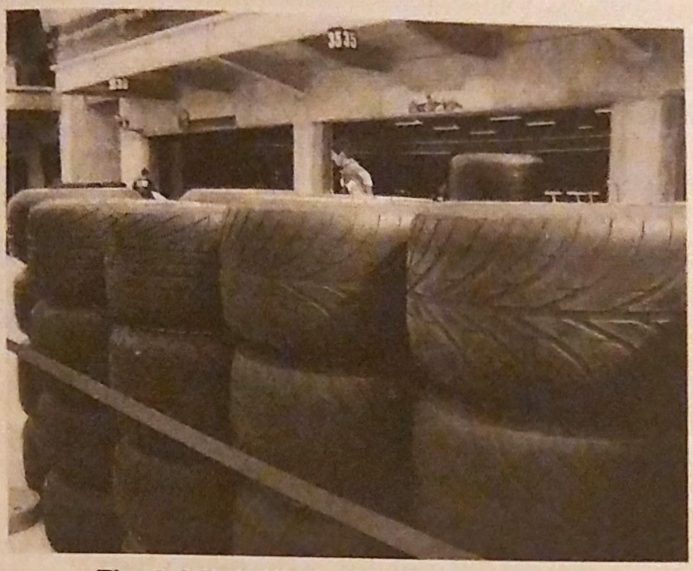

Fig. 9.4 Rain Tires, Wet and Intermediate

at the front of the contact patch. It seems to me that there might be a condition like a standing start where you have some slip, controlled slip, where you might get a better coefficient of friction with a heavier tread."

HH: "Heavier?"

PH: "Yes, a heavier tread because the tread is hitting the ground there."

HH: "Yes, but you need some compromise between the grip and the heat."

PH: "Tire manufacturers have different ways to pre-tension the sidewall plies."

HH: "Uh-huh."

PH: "I've heard that some manufacturers mold the beads farther apart so when the tire is mounted the wheel pulls the sidewalls together to put more tension in the plies. Also in your road tires the mold is flatter in the sidewall area. Do you do anything like that with these tires?"

HH: "Yeah, sometime we use that procedure to control the tension in the sidewall."

PH: "You would like tension in the sidewalls with a lower internal pressure? Is that the reason?"

HH: "Yeah."

PH: "It seems to me that one of the big challenges still remaining is the contact patch, having it work like you would like it to work. Are you using Finite Element Analysis software to work on that?"

HH: "Yes."

PH: "Any other software tools?"

HH: "We use hydro-simulation software."

PH: "What's that?"

HH: "That's a simulation of the wet function so we can decide the tread pattern."

PH: "So you can test tread designs in software."

HH: "That's right. But FEA is not fully developed. We need more accuracy, better correlation between actual and calculated information. In some of the parts we can use it, but in some areas we have to check actual tires as well."

PH: "In that checking, how valuable is machine testing vs. track testing?"

HH: "Recently machine testing volume is bigger than actual testing."

PH: "It's easier to do."

HH: "Yes."

PH: "And then you get the data."

HH: "Yes."

PH: "Do you get full visibility of the team's data?"

HH: "Yeah."

PH: "So they're telling you everything? Because really it looks to me like they have a much better machine to test your tires than you do."

HH: [He chuckles.] "Ha ha ha. Yeah, that's right."

PH: "So that relationship would have to be..."

HH: "Yeah, very important."

PH: "Are you allowed to use more than one compound in the tread?"

HH: "Two compounds here. The France specification we used one compound." [I tried to be more clear about the question. I wanted to know if there could be more than one compound in the tread.]

PH: "For each tire, one compound?"

HH: "Yes, but here we can use two specifications for the dry tires."

PH: "How difficult is it to hit the temperature window here at the Speedway? They ground the track since last year. Did that..."

HH: "It was not a big factor for us."

PH: "I think it was a much bigger factor in May at the Indy 500."

HH: "At the Indy 500 the wear rate was very different from last year and it was a big problem. But we knew already, so it's not a big problem now."

PH: "Would that track grinding make you use a harder compound?"

HH: "Yeah, that's right. However, in the Formula 1 case we have an easier course. The teams don't want us to go to a harder compound."

PH: "How much do you and your people know about the car, the vehicle dynamics, the aerodynamics?"

HH: "Not so much. Still we concentrate on understanding the tire. [He chuckles.] Very strange one."

PH: "Until I began to study this I had no idea that a tire was such a complex device."

I had run out of questions so I thanked Mr. Hamashima for his time. In spite of the language difficulties this interview was more technical than any previous conversation I've had with a person working for a tire manufacturer. It helps to know what questions to ask. Research done for this book made a big difference!

WLF Transform

When I asked Mr. Hamashima if they were looking at track surface textures and the frequency of deformation caused by a road texture he mentioned the "WFL formula" and said it was "really important." Maybe I misunderstood him or he simply transposed the letters, but the WLF transform, developed by Williams, Landel, and Ferry, is an oft-mentioned tool in rubber compound development.

The books I have that describe the WLF transform tend to be confusing, but after reading and rereading them over several years and talking to a few people in the rubber industry, here's my explanation.

Viscoelastic materials display mechanical characteristics that vary with velocity and temperature. If you poke your finger slowly into water you feel no resistance at all, but if you slap your hand down onto the surface it's like hitting concrete. A slow penetration produces a very small opposing force but a quick movement meets strong resistance. This is an obvious speed sensitivity.

Temperature sensitivity can be just as dramatic. Spreading cold butter can be difficult but let it warm to room temperature and it flows readily. Most viscoelastic materials have a characteristic temperature at which their molecular movements require much more external force than at a temperature a few degrees higher. They become glassy below this temperature called Tg, the glass transition temperature. It seems logical that as these materials warm above Tg, their molecular mobility would increase and they would become softer.

It turns out that if you measure a viscoelastic property of a material at one temperature and/or one deformation speed, you can translate that data to a higher speed/temperature condition with a simple arithmetic fudge factor that has several empirically-derived coefficients—the WLF transform. This would be useful in the evaluation of rubber compounds. If you kept track of a number of coefficients and compared the actual performance of your product with the predictive quality of your coefficients, the selection process would continually improve.

Let's say you've got 50 compounds to evaluate. It's cost effective to take room-temperature data on the dynamic modulus, how much force it takes to deform a sample a tenth of an inch at one cycle per second, and then fudge that data for other temperatures and deformation frequencies. More time and more sophisticated equipment would

be necessary to increase the frequency of the deformation and raise the temperature of the sample during testing. Monitoring and controlling all those variables gets expensive.

The WLF transform also eliminates temperature effects when testing rubber samples for friction forces. Sliding a rubber sample on smooth glass or on a textured surface generates heat in the sample if the sliding speed is much above a crawl. The WLF transform allows data taken at slow speeds to be extrapolated to higher sliding speeds.

I think this is another example of the extreme complexity of rubber and tire development. Unlike when working with metal objects, precision engineering is not possible in the development and manufacturing of tires. When Mr. Hamashima said the WLF transform was "really important," he was saying that a relatively imprecise fudge factor helped him develop better race tires.

Ten Ferrari Engineers at Bridgestone?

I missed some of the USGP television programming because I was at the race, but a few days later I heard from a couple of people who said the Speed Channel announcers had reported that 10 Ferrari engineers were resident at Bridgestone. That kind of intimate working relationship is not characteristic of tire manufacturers, so I e-mailed Sarah French to ask if that was true and received this reply:

"No, it's not correct. We have had a reciprocal arrangement this season whereby some of our engineers have visited the Ferrari factory and some of their engineers have visited our technical centre [sic], so we can learn more about the car and they can learn more about tyres [sic]. It was more at the beginning of the season where the car was still being developed. It partly explains why Ferrari have done so well this year because their car is, to a certain extent, built around the tyres."

A few years ago I would have considered her answer to be PR BS, but now I consider it a vast understatement. From my point of view it would have been smarter for Ron Dennis to keep McLaren with Bridgestone instead of switching to Michelin. The well-respected French tire company is handicapped by F1 rules that allow only two tire specifications for each GP. Michelin needs to build tires that work well for their best teams, Williams and McLaren, and those cars are probably different enough to preclude them using the same tire. Making one tire per race for each team means Michelin can't take any chances on a soft compound as can Bridgestone which can make two tire specs for Ferrari. The Japanese company can bring a conservative tire and one more risky. This advantage alone could be worth a couple of tenths of a second a lap.

It's my opinion that Michael Schumacher as a driver is worth a couple of tenths a lap even with the same car and tires as the other drivers. And his feedback on tire development has to be worth another couple of tenths. Any cooperation at all between a racecar manufacturer and a tire company must be worth a fraction of a second a lap. So it's no accident that Michael disappears into the distance at a second a lap as soon as a green flag waves.

It seems to me that McLaren or Williams might be more competitive if they had stayed with Bridgestone and optimized their cars for Michael Schumacher's tire choices. I wonder if Ron Dennis and Frank Williams, the heads of McLaren and Williams, ever thought about that.

Fig. 9.5 Michelin Formula 1 Tires

Barrichello's Tire/??? Incident at the USGP

About 15 minutes into the first practice session on Friday, Rubens Barrichello crashed heavily into the Indy 500 turn-one wall. I was in the media center and watched replays on the TV monitors. He spun to the left suddenly, way before the entrance to the turn and spun across some grass before sliding up the track into the wall, just missing the new SAFER barrier. He was not injured.

The session was red-flagged so workers could remove the car and clean up the debris. Since Barrichello was on an installation lap, his first of the event, this was not a failure of an overstressed part.

The TV monitors showed Barrichello walking down pit lane toward his pits. He was stopped by Patrick Head, William's technical director, and they exchanged a few words before the stocky little Brazilian continued toward his own pit.

As more information accumulated, Ferrari reported the accident's cause as a loss of control because of a loss of pressure in the left-rear tire. Of course their real-time data acquisition transmission would have provided that info and more.

The team seemed to be blaming the tire, and that surprised me. A tire is an extremely strong construction and structural failures are rare. The main culprits in tire failures are low internal pressure, overloading, and heat. None of those conditions could have been present during an initial lap before the high-speed section of the race course.

During the interview included above, Mr. Hamashima said they were still investigating but it was a tire failure or wheel trouble or suspension trouble. Again I was surprised that Ferrari would point any blame at its tire manufacturer, and further surprised that Bridgestone would allow any hint of a tire failure. Since then there has been no additional explanation from anyone. But I was told by an F1 regular that earlier in the year Ferrari had experienced a sudden wheel failure, a sudden explosion of a magnesium wheel due to brake heating.

"The entire story is unintelligible and therefore encourages unintelligible analysis."
—from "The X-Files", FOX TV Network.

CHAPTER 10

TIRE PERFORMANCE DATA

All the forces generated by a racecar work on the track surface through the tires. The racecar generates driving forces through at least one pair of tires, and the driver controls the timing and amount of these driving forces with the throttle as well as exerting braking and steering forces, also through the tires. The goal, of course, is the shortest lap time and the ability to pass other cars during a race. Winning races is the ultimate goal.

There are hundreds of possible adjustments built into a racecar, and the resulting combination of those adjustments called a "setup," determines the interaction between the driver, the racecar, the tires, and the track. The setup is the result of a given racecar and teamwork among the crew, race engineers, and the driver. A team can't test all possible setups on a track and, if they could, there is no guarantee the best setup on one day would work the next day, even at that same track.

Engineers Want More and Better Data

A complete, universal mathematical model of a racecar has not yet been devised, but development continues. Over the years, drivers, crew chiefs, and race engineers have built set-up models in their heads that vary greatly in scope and accuracy, but the common goal is making the car faster. The question bouncing around in all these skulls is, "We want to make the car better, so what do we tweak and in what direction?"

As data-acquisition equipment and data-analysis software became more widely available, and people made improvements in geometry-analysis software and suspension-measurement methods, race engineers began to refine their personal racecar models. Now, if they have the hardware and software and also the time to analyze the data, race engineers know the attitude of the wheels and chassis with respect to the track surface for every lap the car makes. Aerodynamic characteristics of a racecar usually come from the manufacturer and many teams verify these aero maps in their own wind-tunnel tests and make aerodynamic changes to the car's bodywork.

As a result of all these sensors and the computer power on board racecars, engineers know almost everything going on during every lap the car is on the track. It's great to know exactly what a racecar has been doing during a lap just completed. Engineers can look at that data, use complicated software to analyze and present the data, and then be better informed about making changes to the setup. But it would be even better to know what the racecar is going to do before it goes onto the track.

Simulation Software

Engineers continually strive for more detailed information and analysis of whatever problem they're working on. As a result there are now some very complete software simulations of racecars. Almost every aspect of the machine has been reduced to a math model, and in some software products all the components are completely integrated. Prediction of setup changes is one motivation, but money is also involved. Testing a racecar on a track costs thousands of dollars per mile. Testing in a computer is much less expensive.

What you'd like from simulation software is a lap time for a specific setup that can then be duplicated on a specific track. Data from actual laps are used to improve models in the software and the laps are repeated. In some future maybe setup changes can be run in software and then simply verified on a racetrack. If the software gets sophisticated enough, most testing can be carried out in the software

and track testing can be for driver practice and racecar reliability improvements. But this is not going to happen anytime soon and doesn't sound like fun anyway.

I was told by a PhD. who had worked for a race team that the goal of simulation software was to find "non-intuitive islands of performance." By this he meant peaks of racecar performance that couldn't be found by making incremental, common-sense adjustments. He thinks that, given a tire model that's good enough, the right software can find chassis/aero/tire setup combinations that produce quicker lap times than a good team following a test plan driving a car on a track. I asked around about this and decided that finding such a treasure trove is unlikely. And, if you did find such an "island," it might prove to be a mountainous peak and any tiny change in driver, dampers, tires, or ambient conditions might cause a fall down the mountainside, with no path back to the peak.

In general three components of a racecar defy detail analysis: the driver, the dampers, and the tires. Drivers can be trained and cajoled, but personal motivation isn't predictable. I've been told by experienced race-crew people that they can tell if a driver is "on" as soon as the driver arrives at the track for the race weekend.

Damper development continues and few major mysteries exist. But some damper adjustments that produce driver confidence and better lap times can't be confirmed mathematically, and indeed don't show on data from damper dynamometers. And tires remain in the realm of black magic even, or maybe especially, in the minds of tire engineers.

In the 1990s software simulations were available that generated damper forces by looking up force values in a table that contained assumed values for damper forces at some shaft speed caused by suspension movement. Damping forces went up as the suspension moved the damper faster. But in these early simulations tires were still rigid bodies. They might have had a slip angle vs. lateral force table, but the tire was hard as a rock. An elastic tire in a simulation is very difficult, not the least because good data about a tire's elastic response to forces is simply not available.

The data needed for complete software simulation are slip angle vs. lateral force, restoring moment vs. slip angle, braking and driving forces vs. percent slip, tire forces generated under conditions of combined lateral and longitudinal forces, and contact-patch deflection in the three orthogonal directions for all conditions. Equipment to measure these variables at racecar speeds and forces do not exist.

And even if a tire manufacturer somehow tested a tire and provided all the data needed for a complete software simulation, that data wouldn't be correct for the next tire made on that same day. The manufacturing methods used to make tires are simply not precise enough to guarantee every tire performs exactly the same way.

The best simulation software available today can provide acceptable performance comparisons for good-sized suspension changes. Would it be better to adjust the stiffness of the anti-roll bar or use a higher spring rate at that end of the car? If a change like that is made, what should we do at the other end of the car to maintain balance? That's the proper expectations of a software-simulation product. That capability is useful because it saves time and money. And, if the software earns some credibility, there's probably less arguing among the engineers, drivers, and crew chiefs, because people tend to find machines more credible than each other.

At the moment probably the best tire-testing machine is a fully instrumented Formula 1 car. For that reason the best F1 teams (McLaren, Ferrari, Williams) know more about the tires they're using than the people who make those tires. Conversations between the techies at those teams and their tire suppliers must be very entertaining. Oh, to be a fly on the wall!

Typical Tire Data

I'm not supposed to possess or publish tire data without permission from the tire company that made the tires, and they've all refused when asked. I have, however, come in contact with some actual tire data. Let's look at some of it.

This data comes from an open-wheel series operating in the late 1990s. It supplies the following general information about the tire:

Table 10-1: Open-Wheel Spec-Series Radial Tire

	Front	Rear
Rim width, in	9.0 x 13	10.0 x 13
Overall diameter, in	21.80	22.60
Tread width, in	7.25	9.70
Section width, in	9.50	11.40
Pressure, hot, psi	22-26	22-26
Static camber, degrees	-1.5 to -3.5	-1.5 to –2

Spring Rate

Tire manufacturers generate spring-rate data by applying load through the wheel to a tire bearing on a flat plate and recording the radius from the wheel center to the bearing plate. If a 1,000-pound load compresses the tire enough to change the radius by 1 inch, then the spring rate of that tire is 1,000 lb/in.

The spring rate of a tire is important. In a turn, inertial forces generate lateral load transfer from the inside to the outside tires. The tires change radius with loading depending on their spring rate. The outside tires compress and the inside tires increase in radius. The combination causes tire roll which we'll calculate in the next chapter.

The spring rate of the tires determines how they change radius with increased load. Racecars generating aerodynamic downforce add hundreds or thousands of pounds force onto the tires. The underwing of a ground-effects car is extremely sensitive to ride height and rake, the front-to-rear change in ride height. So knowing how a tire responds to vertical loading is important.

This data I'm not supposed to have shows static spring rate for front and rear tires at zero, 2, 3, and 4 degrees camber and inflation pressures of 20, 22, 24, and 26 psi at 18 increments of load from zero to 1,000 lb.

Here's a pair of tables showing part of that data for a front and rear tire. This is the average spring rate from zero load to 1,000 pounds; it's the total change in radius divided by the total change in load. The data detail shows how the tire spring rate varies over that range of load. In the zero-to-200 lb load range the spring rate is higher than the average by over 100 lb/in and lower by a similar amount in the last 200 lb from 800 to 1,000 lb.

Table 10-2: Open-Wheel Front Tire Spring Rate

Camber, degrees	0	2	3	4
Pressure, psi	Spring rate, lb/in			
20	1,162	1,131	1,091	1,077
22	1,207	1,184	1,173	1,156
24	1,281	1,243	1,237	1,213
26	1,210	1,262	1,268	1,262

Table 10-3: Open-Wheel Rear Tire Spring Rate

Camber, degrees	0	2	3	4
Pressure, psi	Spring rate, lb/in			
20	1,072	1,096	1,086	1,045
22	1,141	1,179	1,168	1,146
24	1,213	1,219	1,201	1,179
26	1,111	12,01	1,207	1,184

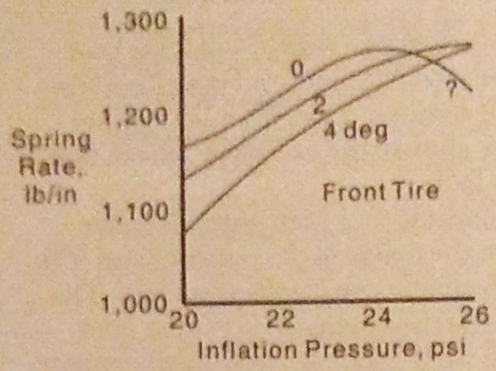

Fig. 10.1 Front Tire: Spring Rate vs. Inflation Pressure

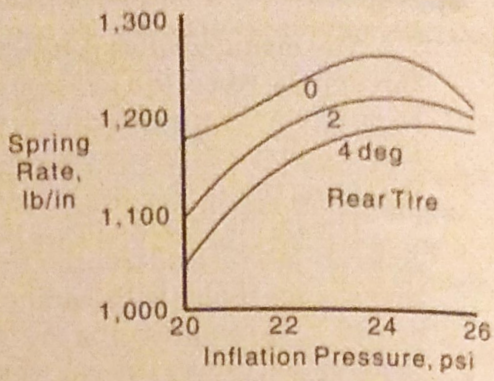

Fig. 10.2 Rear Tire: Spring Rate vs. Inflation Pressure

The graphs generated from the data in these tables show how spring rate varies with inflation pressure and camber. Fig. 10.1 shows front-tire data and Fig. 10.2 is data from a rear tire. At higher cambers the spring rate is lower because the tire is bearing mostly on one corner and tread-belt stiffness is less effective. Remember, the load is opposed (borne) by the internal pressure times the contact patch area. In the graph on the left I put a question mark by what I think is an erroneous data point.

Rolling Radius

For racecars using a low-mounted front wing and the underbody to generate aerodynamic downforce, ground clearance is extremely critical. Changes in ride height by less than 0.030 in. can significantly affect both the magnitude of the downforce and the location of the center of pressure (CP) under the car. The CP is important because longitudinal movement varies the front/rear force distribution due to aerodynamic downforce. When the CP moves forward there's more force on the front tires, and when it moves backward you get more force on the rear tires. So CP movement changes the balance—understeer or oversteer.

The static spring-rate data shown above is well and good, but rolling tires behave differently than static tires and testing tires while rolling is difficult. In addition to the static tire radius vs. load data above, there is rolling radius data in this information I'm not supposed to have, but the data was generated on a test machine using a knurled drum about 6 ft in diameter at relatively low speeds. Data is shown for front and rear tires with an undisclosed inflation pressure for cambers of zero, 2, 3, and 4 degrees and speeds of zero, 12, 35, 60, and 85 mph. Over this speed range the data values don't show much change, and the users of this tire would really like data up to 180 mph. The rolling-radius data given for this tire is of dubious value.

And lateral loading also changes a tire's rolling radius. A tire on a ground-effects vehicle or on a stock car running on a banked track sees huge vertical and lateral forces, both of which decrease the rolling radius. The only way to get data under these conditions is with position sensors in the suspension and laser ride-height sensors—three to fully define the car's ride height and rake—mounted on the chassis. And you still wouldn't know the tire's lateral movement.

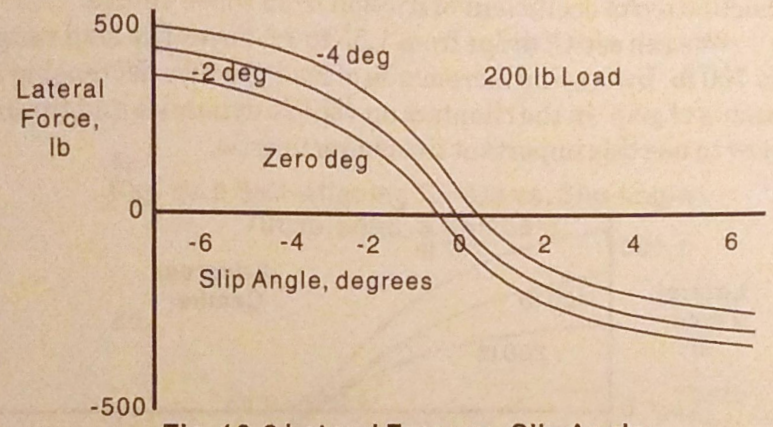

Fig. 10.3 Lateral Force vs. Slip Angle 200 lb Load, 3 Cambers

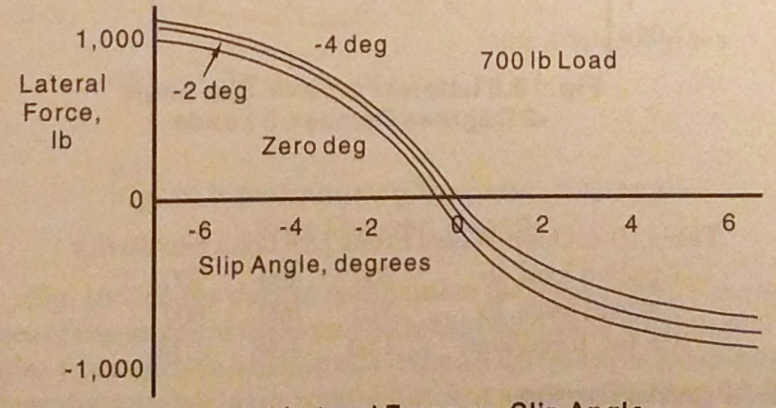

Fig. 10.4 Lateral Force vs. Slip Angle 700 lb Load, 3 Cambers

Lateral Force vs. Slip Angle

Some race tire manufacturers supply performance data in the form of a Microsoft Excel spreadsheet containing raw data and graphs generated from that data. The manufacturer supplying this data I'm not supposed to have tested both front and rear tires while varying inflation pressure, camber, vertical load, and slip angle. Fig. 10.3 and Fig. 10.4 show graphs generated from that data.

Load Sensitivity

Fig. 10.5 illustrates perhaps the most important characteristic of tires—load sensitivity. If you look at where the curves meet the vertical axis you can see the distance between zero and the first curve, the one for 200-lb load, is longer than from there to the next curve, 400-lb load and the next interval from the 400-lb graph to the 700-lb graph is less still. Table 10-4 shows lateral force values at three loads and also a calculation of coefficient of friction from those values.

We can see Cf drops from 1.55 to 1.14 over the load range of 200 to 700 lb. Increasing increments of load produce decreasing increments of grip. In the chapters on vehicle dynamics and tuning we'll see how to use this important tire characteristic.

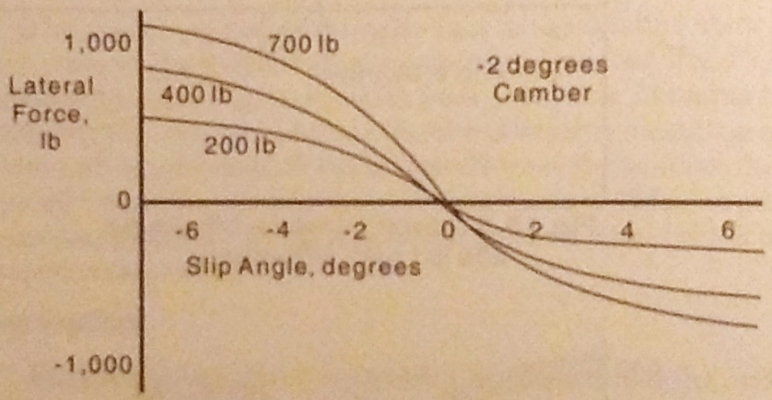

Fig. 10.5 Lateral Force vs. Slip Angle -2 Degrees Camber, 3 Loads

Table 10-4: Open-Wheel Front Tire Load Sensitivity

Applied load, lb	200	400	700
Lateral force, lb	310	590	800
Cf, lat. force/load	1.55	1.48	1.14

Self-Aligning Torque

We described self-aligning torque (SAT) in an earlier chapter and showed its source is lateral force distribution in the contact patch. As slip angles increase SAT increases until the rear of the contact patch goes from stuck to sliding, and the force distribution moves forward, reducing the SAT. Fig. 10.6 contains a graph showing data for three cambers at 700-lb load.

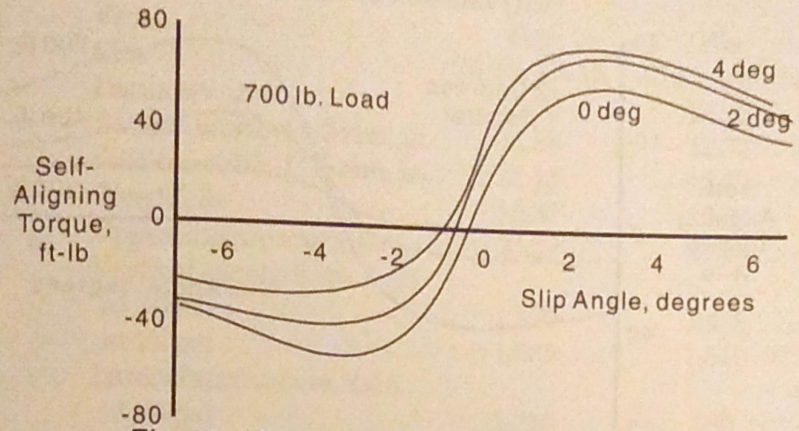

Fig. 10.6 Self-Aligning Torque vs. Slip Angle 700 lb. Load, 3 Cambers

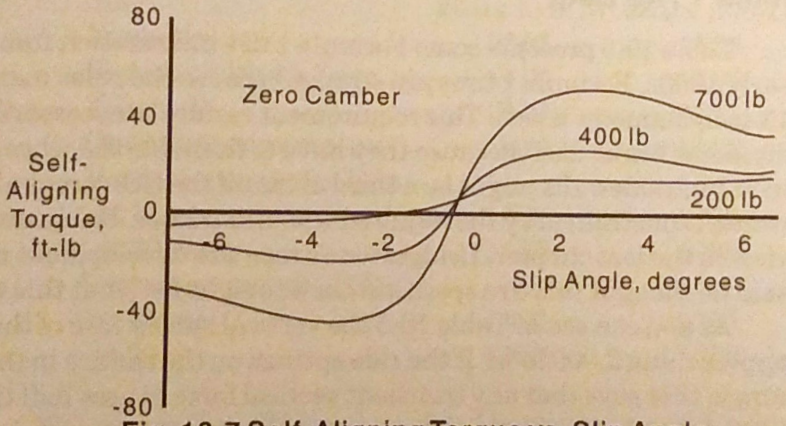

Fig. 10.7 Self-Aligning Torque vs. Slip Angle Zero Camber, 3 Loads

Fig. 10.7 shows data at zero camber for three loads. The significance of the shape of these curves is that SAT falls off at higher slip angles where grip is a maximum. When a driver turns a car into a corner the steering takes some effort, but as slip angle increases, that effort decreases. One of the holy grails of racecar setup is to have the steering torque fall off at maximum grip and give the driver a signal that the grip limit has been reached.

Fig. 10.8 has data taken at –2 degrees camber and three loads, illustrating the asymmetry of camber data. Notice SAT is much higher on the positive side of slip angle than the other. Camber affects the shape of the contact patch and therefore how SAT is generated.

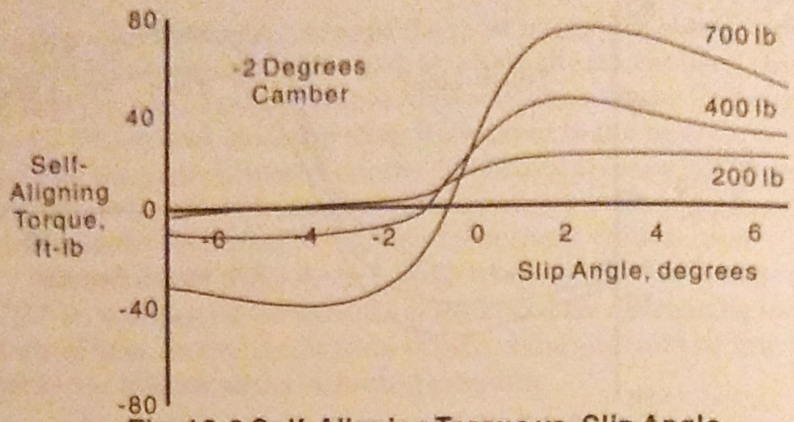

Fig. 10.8 Self-Aligning Torque vs. Slip Angle -2 degrees Camber, 3 Loads

Formula 1 Tire Data

Table 10-5 presents some Formula 1 tire information from the early 1990s. Formula 1 tires are strange because the rules mandate a 13-inch diameter wheel. This requirement results in necessarily small diameter brake discs because they have to fit inside the wheels. The 7-inch-high sidewalls might be a third of that if the tire companies weren't constrained by the required wheel diameter. But in an interview in the last chapter, Bridgestone's race tire development manager said he thought this tire specification was right for F1 at this time.

As you can see in Table 10-5 the vertical spring rate of the tires are approaching 2,000 lb/in. If the ride springs on the car are in that same range, that says that any transient vertical force causes half the car's total deflection in the tires. A racecar engineer's most useful and most adjustable device is the helical coil-over spring and damper. But we see here that the tire accounts for at least half of any vertical deflection, and the suspension damper has no direct control of that tire movement. That seems to be one of the reasons adjustable dampers are seldom used in F1 racecars. The designers' priorities turned to aerodynamic packaging and low CG, both of which discourage a heavy, bulky damper.

Table 10-5: 199? Formula 1 Radial Tire

Front		
Size	Dry	Wet
Diameter, in	25.5 x 9.5-13	25.5 x 10.0-13
Section width-11.0 rim, in	25.43	25.48
Section width-11.5 rim, in	11.88	12.32
Weight, lb	12.15	12.57
Operating pressure, psi	15.80	19.50
Vertical spring Rate, lb/in	20-22	20-24
at 20 psi	1,570	1,455
at 22 psi	1,665	1,510
Lateral spring rate, lb/in		
at 20 psi	1,210	985
at 22 psi.	1,350	1,035

Rear		
Size	Dry	Wet
Diameter, in	26.0 x 13.0-13	26.0 x 13.0-13
Section width-13.7 rim, in	25.95	25.99
Weight, lb	14.96	14.96
Operating pressure, psi	22.31	22.11
Vertical spring rate, lb/in	18-20	18-22
at 18 psi	1,880	1,600
at 20 psi	1,985	1,780
Lateral spring rate, lb/in		
at 18 psi	1,490	1,155
at 20 psi	1,550	1,350

This incomplete F1 tire data that I have, but cannot legally possess or publish, consists of tables and graphs for front and rear tires including one dry and two wet compounds. A typical table presents a data value for lateral force at 13 slip angles from –6 to +6 degrees, including zero degrees. These same data points are repeated for vertical loads of 200, 500, 800, 1,100, and 1,400 pounds for the front tires and 200, 600, 1,000, 1,400, 1,800, and 2,200 pounds for the rear tires. All these data points repeat for inflation pressures of 20 and 22 psi for the front tires and 18 and 20 psi for the rears. They repeat again for negative camber variations of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 degrees for the front tires and 0.5 and 1.0 degrees for the rear tires. That's a helluva lot of data and not really very useful, but I guess team engineers thought it was better than nothing.

The Formula 1 cars in the early '90s were not allowed to have moving skirts to seal the underbodies. They had flat bottoms forward of the rear tires and a large diffuser under the rear wing. The maximum force levels for the tire data testing stated in the paragraph above

give us a glimpse of just how much downforce those cars produced. Double the 1,400-pound test force for the front tires and add that to double the 2,200 pounds for the rears and you get a total of all contact-patch forces of 7,200 pounds. I guess that means a car of that era could corner at 3 Gs ON THE CEILING!

After several rules changes aimed at lowering aero downforce and speeds in corners, today's F1 cars have stepped, flat bottoms and limits on wings and diffusers. But current (2002) cars still produce about 3,500 lb downforce at 150 mph. Almost every F1 team has its own wind tunnel running 24/7, and aerodynamics remains the development area that gives the teams the best return on their money.

MTS Flat-Trac Tire Testing System

In May of 2002 Bridgestone installed in its Tokyo Technical Center what it said at the time was the world's largest tire tester for automotive tires. Bridgestone engaged Minnesota-based MTS Systems Corp. to develop a multi-million dollar version of the patented MTS Flat-Trac LTR tire test system. This is a larger machine with higher load, torque, and speed capabilities than previous tire test systems engineered by MTS.

Over the years, MTS has developed a continuing evolution of Flat-Trac systems, all using sophisticated proprietary application software for control, data acquisition, and data analysis. The machine uses a continuous stainless steel belt to simulate a flat road surface and

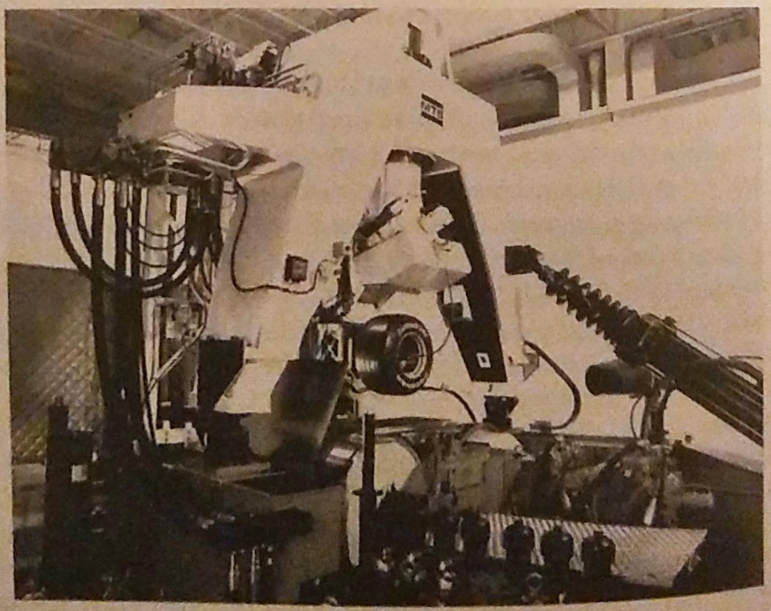

Fig. 10.9 Bridgestone's MTS Flat-Trac Tire-Testing System

provides tire and vehicle manufacturers the tools to acquire critical knowledge of tire behavior while operating at speed, under load, and simulating actual driving maneuvers. Vehicle developers use versions of the Flat-Trac system to match suspension and tire characteristics for optimized vehicle handling and operation.

Bridgestone felt it needed state-of-the-art tire testing equipment to help develop street tires and also to support its participation in the Formula 1, CART, and Indy Racing League series. According to Bridgestone the machine outperforms all other automotive tire testers by far in regard to speed, vertical input, lateral force, and torque. It allows for accurate evaluation of the characteristics of tires while turning, braking and accelerating at high speeds and under heavy loads.

During the interview in the last chapter with Bridgestone's race tire development manager Mr. Hamashima said, "Recently machine testing volume is bigger than actual testing." I'm sure he was referring to the use of this new MTS machine. I didn't know about it at that time, or I would have asked about it. You'd think he'd take that opportunity to brag about his new testing system, but that just shows how reluctant tire guys are to say anything at all.

Table 10-6 Bridgestone's Flat-Trac Specifications:

Tire maximum OD	39.4 in
Tire maximum width	19.7 in
Road speed	200 mph
Slip angle	+/- 30 deg
Inclination	+/- 10 deg
Loaded radius	10-22 in
Vertical load	6,744 lb
Lateral force	+/- 6,744 lb
Longitudinal force	+/- 4,496 lb
Aligning torque	+/- 2,213 lb
Wheel torque	+/- 3,688 lb-ft
Spindle speed	3,200 rpm
Inflation pressure	145 psi
Net drive power	490 hp

Missing information

We didn't include any data on longitudinal forces or slip ratios for braking and acceleration performance because there is none available to me. Critical to tire performance is how a tire responds to a combination of forces—vertical, lateral, and longitudinal. The machine described above can generate that type of data, but I don't think it will be generally available. And this data is only useful after it has been calibrated with on-track tests.

Some of the top race teams in Formula 1, NASCAR, and CART have bought or developed their own simulation software. As these systems become more sophisticated, they run up against a lack of information about the dynamic temperature conditions in a working tire, and how those variables affect grip. A tire at the end of a straight just before hard braking into a slow corner is cool compared to that same tire in mid-corner a few seconds later. Since rubber friction is very sensitive to thermal conditions, we can guess that available grip varies as a tire heats up during each corner. Late in 2002 we heard that at least one tire company was working on a tire thermal model that was complex enough to use up all the computing power at a Formula 1 team.

Motorsports Drives Development

The trend in race sanctioning organizations is toward a spec tire common to all participants. For race series that have gone that route the tire manufacturers are motivated to improve service life, tire-to-tire consistency, and reliability while lowering their costs. Firestone's problems in the U.S with SUV tires notwithstanding, tire companies are supplying us all with road tires that perform superbly in all conditions and provide amazing reliability and service life. Industry-wide overcapacity and poor marketing limit the amount of profit for tire manufacturers, so they just don't have the funds for a massive R&D effort. And why should they spend money for research when their product is working so well? The current Formula 1 tire war between Bridgestone and Michelin might be the major force driving in tire development at this time.

When airplanes became a matter of national security, vast amounts of money flowed into the aerospace industry. Very quickly all the critical components of aircraft were tested and completely characterized: air, wing shapes, materials, manufacturing methods, jet engines, fuels, lubricants, etc., etc. Tires have not and probably never will be seen as important enough for that type of program. For the foreseeable future tire development will continue at a methodical pace driven mainly by competition in Motorsports.

"Lateral load transfer is a bad thing."
—Carroll Smith, page 36 of *Tune to Win*.

CHAPTER 11

BASIC VEHICLE DYNAMICS

We're going to explain vehicle dynamics in this chapter, concentrating on some basic concepts and looking at a few simple calculations. Even though most racers start with a car that someone else designed and manufactured, they can make significant handling improvements by changing spring rates, damper adjustments, anti-roll bars, suspension geometry, and/or roll-center heights. Racers need to understand the effects of changing these components and figure out which direction to go with their adjustments. We're going to lay a foundation in this chapter and the next so the details presented in the last chapter make sense.

We'll present sample calculations that illustrate how lateral and longitudinal acceleration affects weight transfer. If you need to perform more extensive calculations, there are many vehicle dynamics textbooks available. The best by far is *Race Car Vehicle Dynamics* by the Millikens, Bill and Doug.

The Physics: Newton's Laws of Motion

First let's look at the basic physics that applies to a car in a corner. Don't panic; it's as easy as swinging a weight on a string.

Fig. 11.1 should be familiar by now and Fig. 11.2 shows a similar situation. As you swing the weight you can feel it pulling on the string, and the weight would fly straight off if the string broke. The force on the string that holds the weight in its circular flight is described by the equation:

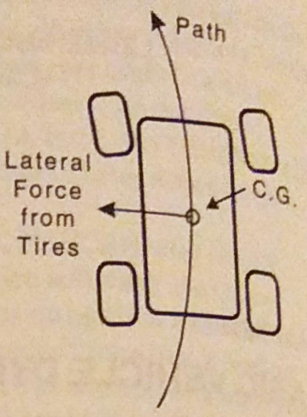

Fig. 11.1 Car on a Circular Path

$F = M \times A$, which reads F equals M times A, where M is the mass (weight, kind of) of an object, and A is the acceleration of that object caused by the force F. This equation is called Newton's Second Law of Motion.

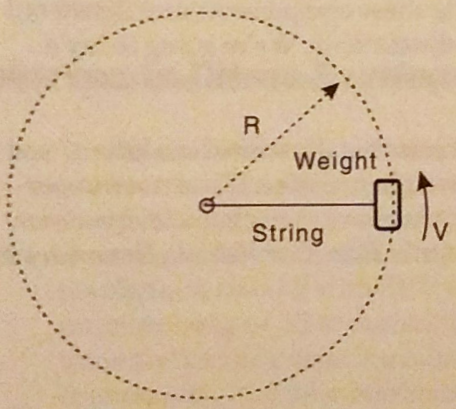

Fig. 11.2 Weight on a String

Sir Isaac Newton, 1642-1727, a British philosopher and mathematician, is famous as the discoverer of gravity. Newton, according to a popular story, was napping under an apple tree and, when wakened by a hit on the head from a falling apple, came up with the idea that there must be a force on the apple that made it fall toward the ground and clunk him on the head. Silly story or not, Newton used his personal observation of natural phenomena to formulate some basic relationships between mass and forces and the acceleration of bodies that are the foundation of all the engineering sciences.

Newton's First Law of Motion: A body at rest will remain at rest, and a body in motion will continue in motion with constant speed in a straight line, as long as no net force acts on that body.

Newton's Second Law of Motion: If a net force acts on a body, the body will be accelerated; the magnitude of the acceleration is proportional to the magnitude of the force, and the direction of the acceleration is in the direction of the force.

Newton's Third law of Motion: Whenever one body exerts a force on another, the second body exerts a force equal in magnitude and opposite in direction on the first body.

The word "net" in these statements is important because there could be a combination of forces of different intensities acting toward various directions. Some of these forces could cancel out others, so it's the result of all their values and directions, the "net" effect, that matters. If the forces on an object add up to zero or if there are no forces acting on an object, the net force is zero and that object is said to be in equilibrium—it's not going anywhere.

Inertia and Units

Bear with me now we need to lay some pipe to make concepts explained later more understandable. We need to get comfortable thinking about inertia, a characteristic property of all objects. Newton's First Law, an object remains motionless or maintains the same speed unless acted on by a force, implies a resistance to movement generally called inertia. This resistance to movement is related to the mass of an object and the Second Law, F = M x A, describes this relationship. F is the force acting on a body and M x A is the inertia opposing that force. F and M x A are equal but acting in opposite directions. Force and inertia have both magnitude and direction, so they are referred to as vector quantities and will be represented in schematics as arrows.

We also need to talk about units. Newton's Second Law states a force is mass times acceleration. In the metric system the force unit is a newton, mass is a kilogram, and acceleration is a meter per second per second. So F (nt) = 1 kg x 1 m/sec^2.

In the British system we use the term pound for both mass and weight. So a pound weight (lb) = a pound force (lbf) = 1 pound mass (lbm) x 32.2 ft/sec^2 which is the acceleration of standard gravity, 1 G. In this book I'm generally going to talk about pounds weight or force and pounds mass. When describing concepts the differences don't matter, but if we do any calculations, the units need to come out right. A 1 lb weight or a 1 lb force (lbf) is approximately 1/32 of a pound mass (lbm).

When any mass is near the surface of our planet, Earth, we say the force of gravitational attraction accelerates that mass with a force of one "G." A G is defined as the force that will accelerate any object at 32.2 feet per second per second (32.2 ft/sec$^{2)}$. If we stand on a scale we can read the result of a 1-G force on our bodies, our weight. Since F = M x A, our mass, proportional to our inertia, is our weight divided by G. A body weighing 200 lbf has a mass of 200/32.2 = 6.21 lbm.

F=MA for a Circular Path

For an object in a circular path, our weight tied on a string for example, the Second Law equation remains the same but is written a little differently:

$Fc = M \times V^2 / R$.

Which reads F sub c equals M times V squared divided by R. Fc is the force in the string, called the centripetal force, which is accelerating the weight toward the center of the arc. M is the mass, V is the speed of the object, and R is the radius of the object's circular path. As seen in Fig.11.3 the centripetal force, Fc, is opposed by the inertial force, also called the centrifugal force, which is part of the force you feel when you hold the string.

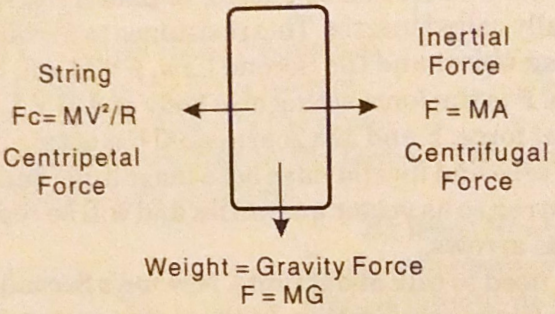

Fig. 11.3 Forces on the Weight on the String (approx.)

Sorry to get complicated, but that first schematic is not quite right. If you've ever actually swung a rock on a string you know the string never gets straight out parallel to the ground. Fig. 11.4 shows why. The string has to support the weight of the rock as well as the inertial force generated by the rock's speed on the circular arc. If I move the weight vector from the rock's CG to form a triangle with Fc and the string, you can see the resultant angle. As the rotating speed goes up the inertial force also goes up, as does the string tension. The weight stays the same but gets smaller in proportion to the other two forces. So, as you swing the rock faster, the angle between the ground and the string gets smaller, but it never gets quite parallel to the ground. Hopefully that short diversion gets me some points with the engineers reading this without confusing everyone else.

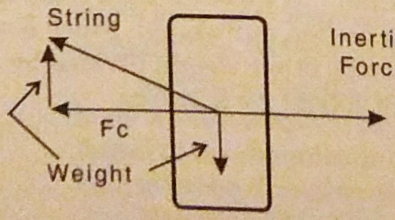

Fig. 11.4 Actual Forces on the Weight on the String

This $Fc = M \times V^2 / R$ equation also applies to a car traveling in a corner of constant radius R and, of course, at an

instantaneous point in time any path can be described as a circular arc with a radius R. M is the mass of the car and V is the speed. If you consider the car to be a big weight with a strong string hooked to the center of mass of that weight, Fc is the sum of the forces generated by the tires. It's those tire forces that keep the car going at that speed on that radius.

Look at the relationships described by this equation:

$Fc = M \times V^2 / R$.

If M gets bigger, Fc has to be bigger or the two sides of the equation are no longer equal. The implication for a vehicle is that a heavier car takes more force to maintain its speed on a given radius than a lighter car.

Now look at V, the speed in the corner. As V gets bigger F also has to get bigger. But V is squared, multiplied by itself. So, when V doubles, the Fc required to hold the car in the turn goes up by a factor of four. As R, the radius of the turn, increases, Fc decreases because R divides into M times V^2, and a bigger R makes that side of the equation smaller.

In everyday terms this equation says a lighter car going slower in a bigger radius corner needs less force to hold that turn. As we said it's not a string, but the tires provide the force to keep the car traveling on that radius. If you want to go fast in tight corners, you need a light car with good tires.

Inertial Forces and Lateral Weight Transfer

Fig. 11.5 and Fig. 11.6 are a couple of silly drawings depicting an inertial situation, but they illustrate something I'm going to try to explain later. You've put your blow-up clown doll in your wagon, but when you pull on the wagon, the clown doll rolls backward, and if you're not careful, it will fall out of the wagon.

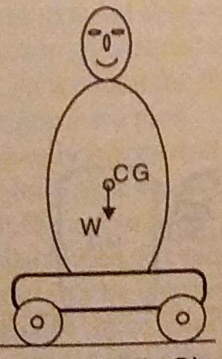

Fig. 11.5 Static Clown Doll In Wagon

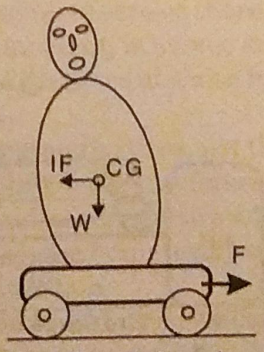

Fig. 11.6 Force Accelerates Wagon, Inertial Force Rotates Clown Doll

Technically but simplified, what's happening when you pull on the wagon is a force is transferred from the wagon bed to the doll by friction, and the doll moves along with the wagon. We can say all the doll's mass is at its center of gravity (CG), and the inertia of that mass resists the acceleration of the wagon/doll. Because the CG of the doll is above the wagon, this inertial force, IF in the drawing, rotates the doll around its bottom.

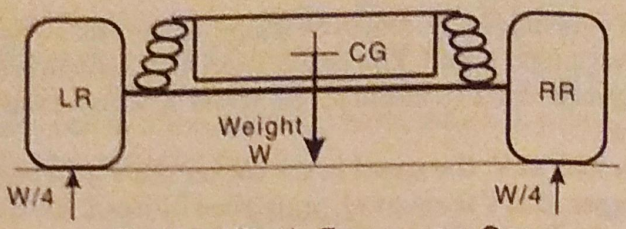

Fig. 11.7 Static Forces on a Car

A car sitting still is like the weight before you start to swing it on the string or like the doll sitting in the wagon. The schematic in Fig. 11.7 shows the forces on a static car. This is an end view, obviously, with only two tires shown. The weight (W) of the car is evenly distributed among the four tires, so each tire has W/4 force on its contact patch. The total weight, W, never changes. The tire patch forces stay the same, W/4, as long as the car is sitting still or going in a straight line at a steady speed, but the weight on each tire patch starts to change as soon as the car begins to brake, accelerate, or turn a corner.

We know now that the tires generate the centripetal force that turns a car. Those tire forces are generated at ground level where the rubber meets the road and are accelerating the car toward the center of the turn. The mass of the car, however, is generating an inertial force resisting this acceleration, and that inertial force changes the distribution of the car's weight among the contact patches.

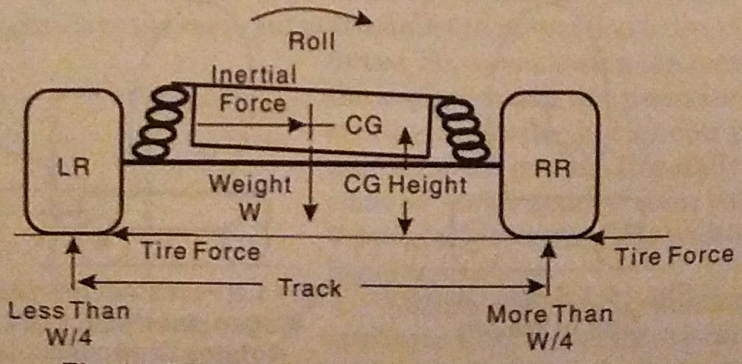

Fig. 11.8 Forces on a Car in a Left Turn

Fig. 11.8 shows the forces acting on a car in a turn. The tire forces are pushing on the tires at ground level, but the center of mass of the car is above ground level. The inertial force is resisting the tire forces and is trying to topple the car toward the outside of the corner, causing the car to roll on its springs, as we all have experienced. The weight of the car is the same, but the inertial force changes the distribution of that weight.

The W/4 weight that was on each tire patch increases on the outside tires and decreases on the inside tires. This is what we're calling weight transfer. In more rigorous technical circles this is referred to as load transfer to differentiate it from the weight transfer occurring due to the lateral movement of the CG with roll. But we're trying to explain the concepts rather than get into the technical detail. Since we're not going to worry about the CG moving in roll, contact patch force changes due to inertial reactions during cornering are called weight transfer.

Weight Transfer Calculation

We can calculate weight transfer, but we have to know a few details first. We need to know the static weight at each wheel, the width between the centers of the contact patches called the track, and the height of the center of gravity or CG.

We're working with only one pair of tires in Fig. 11.9 as if the car's weight is evenly divided on all four contact patches. Let's say the car weighs 2,000 lb so there's 500 lb on each tire patch. The track is 50 in and the CG is 16 in high.

Engineers are taught to look for simple ways to calculate unknown quantities, and summing moments (similar to torque) is the concept we'll use here. Our schematic in Fig. 11.9 shows a pair of tires with forces acting on them, but there is no movement so all the forces must cancel each other out. We can choose a point on the car, and all the torques around this point must add up to zero or there would be some rotation. A torque, also called a moment, is a force acting at a distance, so we look for forces and the distance of those forces from whatever point we pick.

We're only interested in the weights on the tires, not the tire forces, so let's pick a point through which those tire forces are acting. Point Z at the center of the contact patch of the left tire will work. W_L and the tire forces go through Z, so they don't create any moments about Z and can be ignored in this calculation.

There are three moments we need to add up so we can solve for W_R:

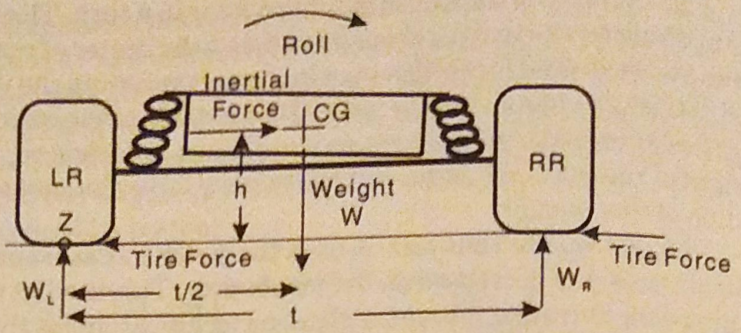

Fig. 11.9 Calculating Forces in a Left Turn

The first moment, acting counterclockwise, is W_R times the distance from W_R to point Z which is the track, t. Another moment acting clockwise around Z is the total weight, W, which is a distance t/2 from point Z. The inertial force, W x A, is also acting clockwise at the CG. So here's our sum:

$W_R \times t = W \times t/2 + W \times A \times h$.

The A is the acceleration caused by the tire forces that are holding the car in a circular path and creating the inertial force, W x A. A is in the units of G, a unit of gravity that accelerates everything at 32.2 ft/sec^2. If the tires are turning the car at 1 G the equation is this:

$W_R \times 50$ in = 1,000 lb x 25 in + 1,000 lb x 1 G x 16 in.

$W_R \times 50$ in = 25,000 + 16,000 = 41,000 lb in.

W_R = 41,000 lb in / 50 in = 820 lb.

That 820 lb is the calculated W_R due to 1 G of acceleration in a corner. Since the total weight on both contact patches is still the same we can now calculate W_L.

$W_L = 1{,}000 - W_R = 1{,}000$ lb – 820 lb = 180 lb.

A total of 320 lb were transferred from the inside tires to the outside tires. The 500 lb on the left tire became 180 lb and the 500 lb on the right side became 820 lb.

Fractional Weight Transfer

Let's go back and look at our equation that sums the moments about Z.

$W_R \times t = W \times t/2 + W \times A \times h$.

If we divide both sides of the equation by t we get:

$W_R = W/2 + W \times A \times h/t$.

And, if we subtract W/2 from both sides we get:

$W_R - W/2 = W \times A \times h/t$.

We also know that this car has equal static weight distribution side to side, so we can write another equation that is also true. The weight transferred is our new right-side, single-tire weight, W_R, and the total weight transferred for the car is W_R subtracted from half the total weight of the car:

The weight transferred = $W_R - W/2$, which is the last equation above. So:

The weight transferred = $W_R - W/2 = W \times A \times h/t$.

The weight transferred expressed as a decimal fraction of the total weight, which we're calling the Fractional Weight Transfer or FWT, is:

$FWT = A \times h/t$.

This gives you the fraction of the total weight transferred. Using the numbers in the example above:

$FWT = 1.0 \times 16 / 50 = .320$.

This means that W_R gains 0.32 times 1,000 lb or 320 lb, becoming 820 lb. And W_L loses 320 lb, becoming 180. Multiplying the FWT result by 100 give you the weight transfer in percent.

This last equation, $FWT = A \times h / t$, shows that the weight transfer is proportional to the acceleration in Gs and the height of the CG and is inversely proportional to the track. So weight transfer increases with the weight of the vehicle and the CG height and it decreases with a wider track.

CG and Lateral Weight Transfer Examples

This table uses the FWT equation above to calculate the percent weight transfer for several types of racecars—Formula 1, CART, and Winston Cup (WC). I'm estimating the CG and also showing a varying CG height for the Winston Cup car just to show the effect of a small change. The wheelbase doesn't matter in this calculation, it's there for comparison.

Table 11-1: $FWT = A \times h / t$

	F1	CART	WC	WC	WC
Weight, lbs	1,500	1,800	3,600	3,600	3,600
Wheelbase, in	120	120	110	110	110
Track, in	60	68	70	70	70
CG height, in	12	14	16	15.5	15
Lat. accel, Gs			Wt. transfer, %		
1	20.0	20.6	22.9	22.1	21.4
2	40.0	41.2	45.7	44.3	42.9
3	60.0	61.8	68.6	66.4	64.3

Tire Roll

Tires have a spring rate, so there is some chassis roll due to tire deflections. In the example above, assuming a tire spring rate of 1,000 lb/in, the right-side tires gain 320 lb each, and would deflect by 0.32 in. The inside tires would rise by a like amount. This roll is contained totally by the tires and is not controlled by ride springs or anti-roll bars.

Longitudinal Weight Transfer

Referring to Fig. 11.10, we'll take a look at longitudinal weight transfer due to braking. Longitudinal weight transfer due to acceleration is calculated exactly the same but in the other direction. The weight of the car, W, at the CG is opposed by the tire forces at the four contact patches. Ignoring aerodynamic forces, we can say that the change in weight from the rear to the front contact patches is equal to the inertial force acting at the CG opposing the tire forces that are slowing the car.

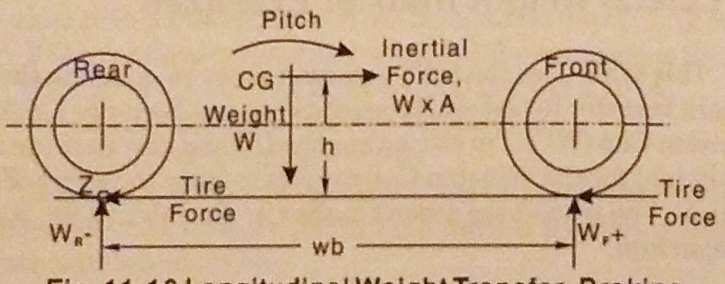

Fig. 11.10 Longitudinal Weight Transfer, Braking

If we sum moments around point Z in the center of the rear contact patches we have the change in contact-patch force at the front tires times the wheelbase, Wbrake x wb, equal and opposite to the moment caused by the inertial force at the CG, which is the car weight, W, times the acceleration caused by braking, times the CG height, h. The equation is:

Wbrake x wb = A x W x h.

Rearranging, we get an expression similar to the equation for lateral weight transfer.

Wbrake = A x W x h/wb.

The weight transferred due to braking is proportional to the acceleration caused by braking and the vehicle weight and the CG height and is inversely proportional to the wheelbase. Using the same car as in the lateral weight transfer calculation, we have a 2,000-lb car with equal static weight distribution, the wheelbase is 100 inches, and the CG is 16 in high. For braking at 1 G we have:

Wbrake = 1.0 G x 2,000 lb x 16 in / 100 in = 320 lb.

During braking at 1 G, 320 lb comes off the rear tires and onto the front tires. Static weight distribution was 1,000 lb on the front and the same on the rear. Now we have 680 lb equally divided between the rear tires and 1,320 on the front two tires.

This change in weight distribution due to longitudinal acceleration causes changes in spring and tire loads in the same way as lateral weight transfer. The car pitches forward as the rear springs elongate and the fronts compress. Tire deflection also occurs. Suspension geometry and changes in CG height due to longitudinal acceleration or braking have effects, but won't be examined here.

Suspension 'Anti' Geometry

As with lateral forces, chassis roll, and lateral weight transfer, similar relationships exist with longitudinal forces, chassis pitch, and longitudinal weight transfer. Basically the tire forces act at ground level and cause inertial forces acting at CG height. The resulting moment causes weight transfer. To some extent, suspension geometry can lessen the amount of pitching forward, front-end dive, under braking and rear-suspension compression, squat, due to acceleration.

Anti-Dive and Anti-Lift with Braking

Fig. 11.11 shows how, in the side view of the car, we can draw lines through the chassis pivot points of the front suspension links and find, at their intersection, the instantaneous center of rotation, IC, for the front suspension. We can then construct the side view swing arm, SVSA, of the front suspension by drawing a line (dotted) from the IC to the center of the contact patch of the front tire. This line makes an angle with the ground that is defined by the ratio of the SVSA height divided by the SVSA length. This is the angle that determines the amount of anti-dive geometry in the front suspension of a vehicle with outboard brakes. Inboard brake forces are handled the same as anti-squat, described in the next section.

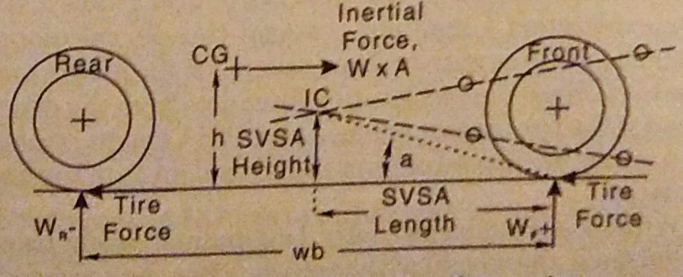

Fig. 11.11 Front Anti-Dive Geometry

If the IC is at ground level the SVSA ratio is zero; there is no anti-dive present; and the vehicle pitches forward, compressing the front springs as the rear springs extend. As geometry adjustments raise the height of the IC from ground level, anti-dive forces go up. When SVSA height equals its length, there are no pitch forces and no change in spring length in the suspension during braking. This condition is called 100% anti-dive, and the inertia force goes through the suspension linkages directly to the contact patch with no pitch moment.

Racecars have a front/rear brake bias adjustment, usually placed in the cockpit, so brake-bias changes can be made by the driver. This adjustment controls the proportion of braking between the front and rear tires and so must be taken into account when calculating front anti-dive forces.

The total change in front/rear contact patch forces as described in the previous section is A x W x h / wb. With anti-dive geometry the actual change in loads is A x W x SVSA height / SVSA length x % front brake bias. To get percent anti-dive we need to divide the actual by the total:

Percent anti-dive = (A x W x SVSA height / SVSA length x % front brake bias) / (A x W x h / wb).

The A x W terms cancel each other and we can multiply by the inverse of h / wb:

Percent anti-dive = % front brake bias x SVSA height / SVSA length x wb / h. We can recognize that SVSA height / SVSA length is the tangent of angle "a" in the schematic and simply further to:

Percent anti-dive = % front brake bias x tan a x wb / h.

For the example above of a 100-inch wheelbase and a CG at 16 inches with 60% front brake bias and SVSA height / SVSA length = 0.10:

Percent anti-dive = 60 x 0.10 x 100 / 16 = 37.5%.

If the rear suspension geometry has its IC inside the wheelbase with the same SVSA height / length ratio as in the example above, that end of the car will generate the same percentage of anti-lift under braking.

Anti-Squat with Acceleration

Suspension geometry also affects front/rear force distribution under acceleration. Longitudinal weight-transfer calculations are exactly the same as with braking except for the absence of percent brake bias. Since the acceleration force acts from the drive shafts instead of the tire contact patches, the SVSA height is taken from the wheel center up instead of from the ground up as in the anti-dive calculation.

Without anti-squat geometry, longitudinal weight transfer is the inertial force, the weight of the vehicle times the acceleration in Gs, times the ratio of the CG height to the wheelbase:

Wacceleration = W x A x h / wb.

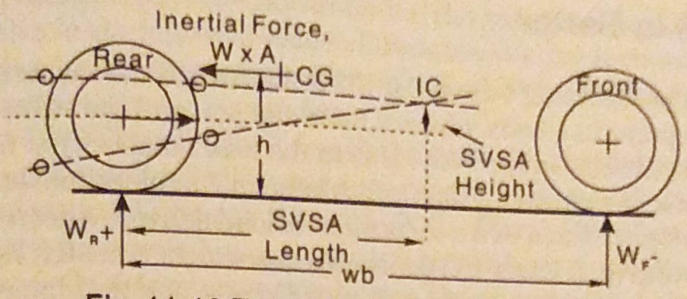

Fig. 11.12 Rear Anti-Squat Geometry

The anti-squat force generated by suspension geometry is proportional to the angle between the IC and the horizontal line through the center of the rear wheel. This angle is defined in Fig. 11.12 as SVSA height / SVSA length.

Wanti-squat = W x A x SVSA height / SVSA length. Percent anti-squat is the anti-squat force divided by the total weight transfer times 100.

Percent anti-squat = 100 x (W x A x SVSA height / SVSA length) / (W x A x h / wb). Once again the W x A terms cancel out and:

Percent anti-squat = 100 x (SVSA height / SVSA length) x (wb / h).

Again we can recognize that the SVSA ratio is the tangent of the angle between the line from the IC to the wheel center and a level line from the wheel center.

Percent anti-dive = 100 x tan a x wb / h.

Calculating with the same numbers as above:

Percent anti-squat = 100 x 0.10 x 100 / 16 = 1,000 / 16 = 62.5 %.

Anti Trade-Offs

As always there are trade-offs. Notice in Fig. 11.11 that the dotted line drawn between the IC and the contact patch is the instant radius of motion of the contact patch, indeed of the whole wheel. Any movement of that wheel has to be instantaneously perpendicular to that line. The car is moving to the right and a bump causes the wheel to move up and toward the bump. That's the opposite of compliance and adds to ride harshness, a problem more with road cars than racecars.

Wheel movement in bump decreases SVGA height, changing the ratio that determines percent anti. Will wheel travel reduce the desired anti until it disappears? With enough wheel movement, antis could become pros. Pro-dive would increase forward pitch under braking, and pro-squat would amplify pitch down at the rear.

Notice also that anti-forces increase with inertial forces. A high-downforce racecar can generate more than 3 Gs under braking, so anti-dive forces can be huge at initial braking and then fall off as air speed bleeds off during deceleration. The extra forces in suspension linkages can cause excess friction, so in practice, anti-geometries seldom exceed 50%.

Lower CG Is Better

The Center of Gravity or CG is also called the center of mass. This is the point in a body where a force can act, and the effect is the same on all particles in the body. Due to the load sensitivity of tires, weight transfer in a corner or during braking and acceleration decreases overall grip. Each extra increment of load delivers a decreasing increment of grip. A lower CG generates less weight transfer, resulting in more equal load on inside and outside tires, and that improves overall grip. Racers should do everything within the rules to lower weight on their racecars.

Current (2002) Formula 1 designers have taken this to the extreme. Some are using more than 200 pounds of ballast (tungsten blocks) and have specially designed their chassis to facilitate moving ballast around for small adjustments in balance. They don't want to use anti-roll bars to adjust balance because ARBs transfer even more weight across an axle and kill more grip. (We'll look at that situation in detail later.) Millions of dollars are spent to lower the overall weight of the car in pursuit of more ballast. F1 engine manufacturers are designing engines with wider-angle Vs to lower CG.

Think about it. F1 teams get tires and engines from other organizations, so they have little control over those components. Most F1 teams have their own wind tunnel running almost full time, producing improved aero bits weekly. One of the few areas a team can attack with full control is their car's weight distribution. They make their own chassis, so they have control over the weight of every component.

The FIA came up with a great rule a few years ago when it decreased the maximum allowable track of the F1 cars. You can see in Table 10-1 a few pages back that, although the CG of an F1 car is lower than the other examples, the weight transfer percentage is not that much less. That rule change decreased grip by increasing weight transfer and had the added effect of the tires being closer to the bodywork where their turbulence decreased the overall aerodynamic efficiency, slowing the cars even more.

CG Is Important: Winston Cup Cars at Martinsville

Martinsville Speedway in Southern Virginia is just over a half-mile in length with only 12 degrees of banking in the corners. As a result of a tight turning radius and small bank angle, the racecars spend a significant part of their lap time rolling through the middle of the corners. This requires the cars be balanced well and the driver needs to keep the tires at maximum grip without losing control.

Suspension setups are extreme at Martinsville. The teams put 7 or 8 degrees of camber in the front tires, negative on the right and positive on the left. The top of the left-front tire juts out of the wheel well.

When the crew rolls the car around in the garage area, you can see wrinkles in the left front sidewall because the tire is cocked up on its outside corner. Due to weight transfer and pressure build up, the cold inflation pressures are very low.

In 1998 Terry Satchell was the engineer on Ken Schrader's Skoal-sponsored number 33 Winston Cup car entered by Andy Petree Racing. When I visited APR near Asheville, N.C., Terry showed me some simulation software he was using to help with setup choices. Terry was able to easily change some numbers in the program, and the results shed some light on the importance of a car's center of gravity (CG).

Without changing anything else in the software model of the racecar, Terry raised the CG of the car from 15.5 to 16.5 inches above ground. The simulation software said the lap time at Martinsville went from 20.300 seconds to 20.415. On race weekend Ernie Irvan was on the pole at Martinsville with a time of 20.229 seconds. Ted Musgrave earned the ninth spot on the grid with a lap time of 20.415 seconds.

The simulation revealed other details resulting from the higher CG. The top speed on the straight slowed from 112.0 mph to 111.6. Mid-corner speed in Turns 1-2 went from 62.9 to 61.6 mph and from 60.3 mph to 59.7 in Turns 3-4. The sim showed the car pushed more in the corners due to the higher loading of the right front tire. The change in loading also made a difference in the location of the front roll center in the turns.

So CG is critical. That's one reason why the most serious NASCAR teams manufacture their own chassis. The lighter they can make the overall car, the more lead ballast they can use to lower the CG. That's also the reason you see the drivers sitting as low in the car as possible.

Typical Independent Suspension

The schematic in Fig. 11.13 describes a typical independent suspension using A-shaped control arms that are non-parallel and of unequal length. These last two descriptors are important because

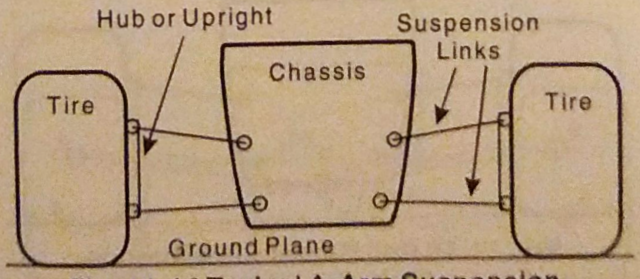

Fig. 11.13 Typical A-Arm Suspension, Unequal-Length, Non-Parallel

equal-length, parallel control arms cause the tires to roll about the same amount as the chassis rolls. Since we'd like to have the tires upright most of the time, this type of suspension is of no use.

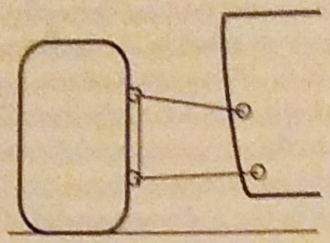

Fig. 11.14 Single-Tire, Fore-Aft View

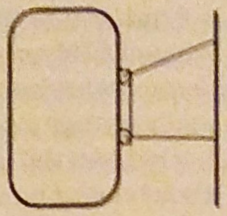

Fig. 11.15 Single-Tire, Top View

Fig. 11.14 and Fig. 11.15 provide a couple of different views to show a better overall picture of this type of suspension. We're not showing a spring or damper, just the important links. If this were a rear suspension there would be a driveshaft and if it were a front suspension we'd include a steering link.

Roll Centers

The concept of instant centers in the kinematic design of linkages can be very complicated. We're going to use it here as a way to simplify the analysis of tire and suspension forces.

The roll center can be thought of as the instantaneous center of rotation of a set of linkages. In theory the instant center we're constructing is the point around which the chassis rotates when it rolls. But more useful, I think, is the Society of Automotive Engineers (SAE) definition that it is the point at which lateral forces may be applied to the sprung mass without producing suspension roll. So, for our purposes here, the roll center is the action point for the tire forces acting on the car.

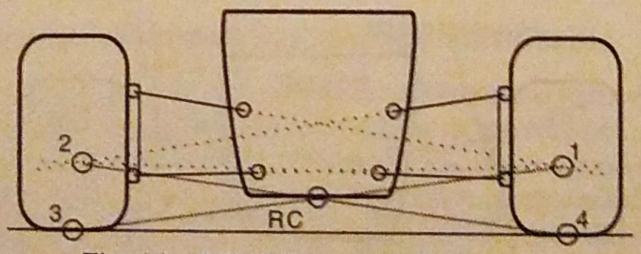

Fig. 11.16 Roll Center Construction, Static Conditions

The drawing in Fig. 11.16 shows the construction of the roll center for this suspension under static conditions. First, extend lines along the upper and lower suspension links until those four lines intersect at two points, 1 and 2, on either side of the car. From points 1 and 2 draw lines to the center of the contact patch of the tire controlled by those two links. The contact patch centers are shown as points 3 and 4.

The point of intersection of the lines drawn from points 1 and 2 to points 3 and 4 is the roll center (RC). This is an instantaneous roll center and was constructed at the static position.

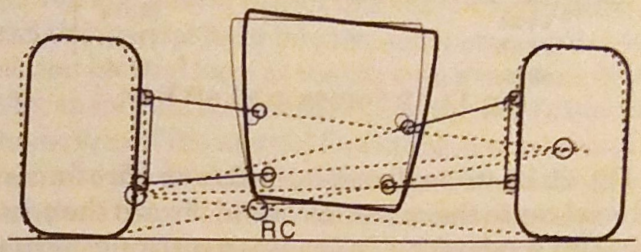

Fig. 11.17 New Roll Center after Chassis Roll

Fig. 11.17 shows what happens when the car turns left, the chassis rolls, and the suspension moves. We have a new roll center, and we didn't do a very good job of camber control since both tires moved into less productive camber for a left turn.

This new roll center was constructed using the same contact-patch point as in the static case, and we know that a contact patch moves around as lateral and longitudinal forces vary. The precise analysis of roll centers is very difficult.

Cornering Forces

Let's go through a set of schematics similar to those earlier in the chapter but showing an independent suspension. This first one, Fig. 11.18, depicts static forces on the car. The weight of the car at the CG

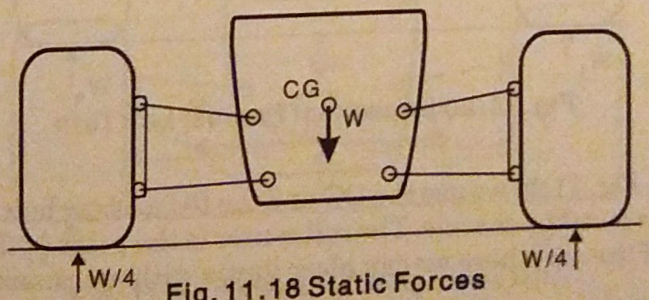

Fig. 11.18 Static Forces

bears on the ground through the four tire-contact patches. We're obviously assuming equal weight distribution among the four tires and only showing two of them.

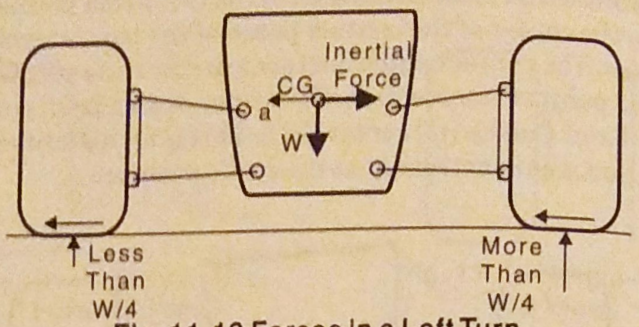

Fig. 11.19 Forces In a Left Turn

In Fig. 11.19, we see forces in a left turn. Tire forces acting at ground level cause the car to accelerate toward the center of the arc of the turn. This acceleration, "a," causes a resisting inertial force acting at the CG. Since this inertial force is above the ground, it tries to roll the car toward the outside of the turn. The magnitude of the force times the distance from the CG to the ground is called the "overturning moment" which causes weight transfer from the inside tire contact patches to those on the outside of the turn.

Total car weight, W, acts downward from the CG and is countered by tire loads which are now unequal due to the weight transfer. This illustrates an important point. The total weight of the car still has to be supported by the sum of the contact patch forces even if the distribution of the car's weight changes among the contact patches.

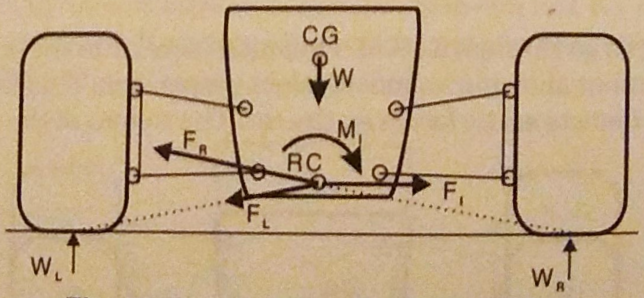

Fig. 11.20 Equivalent Forces, Left Turn

In Fig. 11.20 we use the CG and the RC to show how the tire forces act on the chassis. The roll center is the point in the fore/aft view of the car where we can place forces without causing roll. This

fact lets us perform an engineering trick that will help us visualize and eventually calculate weight transfer caused by the inertial reaction to the tire forces.

Fig. 11.20 is force equivalent to Fig. 11.19. We've replaced the forces generated by the tires with their equivalents—F_R from the right tire and F_L from the left tire—acting from the RC in a direction determined by the suspension geometry. F_R is larger than F_L because weight transfer has shifted load to the right tire and it's generating more grip than the lesser-loaded left tire.

The inertial force at the CG caused by lateral acceleration results in chassis roll and lateral weight transfer. Our engineering trick has separated the inertial force into two separate components. We've replaced that inertial force at the CG with a moment, M_I, around the RC and F_I, an inertial reaction to F_L and F_R. The CG-to-RC distance is the moment arm of the inertial force so M_I has a value of the inertial force, F_I, times the distance between the CG and the RC.

Since the CG-to-RC distance determines the magnitude of M_I, the position of the RC determines the roll behavior of the car. If the RC is a lot lower than the CG, the moment arm is longer and the chassis wants to roll more. If the RC is high, the CG/RC moment arm is shorter and the roll moment is less. The inertial force varies with the mass of the chassis and the amount of acceleration generated by the tires holding the car in the corner, so those variables also affect roll behavior.

Jacking Force

The relationship between the RC and CG has another trade-off we'll show in the schematic in Fig. 11.21. We've added the two tire forces together into F_T and resolved that vector sum into horizontal (F_H) and vertical (F_V) components which we're calling the relevant forces. The dotted-line arrow explains how F_V is derived, while the solid-arrow F_V shows it acting at the RC. The result is the same as in Fig. 11.19 and 11.20 but separating the sum of the tire forces into horizontal and vertical components illustrates another consequences of RC height.

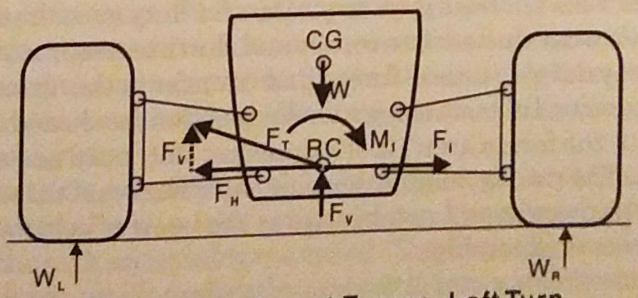

Fig. 11.21 Relevant Forces, Left Turn

The horizontal component of the tire forces, F_H, acts toward the center of the circular path of the car and accelerates the car so it can travel on that path. And F_V, called the jacking force, acts at the roll center, raising the car, which is how it earned its name.

F_H is the force that causes the inertial reaction at the CG that we've transformed into a moment, M_I, around the RC and an inertial force, F_I, at the RC.

Roll Center Position Trade-Offs

Suspension-link geometry determines RC location, which can be above the CG, below the ground, or out past the tires. The importance of the RC is it determines the split between the jacking force and the roll moment. A high RC has a short moment arm for F_I, the inertial force opposing F_H, so the roll moment, M_I, is small. But to get that RC high the suspension link geometry creates a bigger F_V, which is the jacking force.

An RC at CG height creates no roll moment but a lot of jacking force. If RC is higher than the CG, roll forces reverse and the body/chassis rolls into the turn but jacking forces get even bigger.

Going the other way, a low RC creates a big roll moment but less jacking force. If the RC is below ground level, jacking forces are negative, and the car squats at that end when it turns.

Since roll center location determines how tire forces react on the car, the geometry of the suspension links should be chosen carefully if for no other reason than the desire to prevent sudden force changes during suspension movement. And roll-center location determines the distribution of roll forces between the front and rear tire-pairs which affects balance—oversteer or understeer. We'll look at that in detail in the chapter on tuning.

Timing of Forces

The graph in Fig. 11.22 describes a powerful concept that filled a big hole in my understanding of vehicle dynamics. Claude Rouelle explained this to me a few years ago, as he was developing his highly-successful seminar on vehicle dynamics. This graphic shows the reason you see all those guys in pit lane fiddling with the shocks!

When a car turns into a corner and the tires assume some slip angle, they develop lateral forces that transfer to the chassis through the suspension links, causing inertial reaction forces and a roll moment. But the forces aren't instantaneous; they need some time to build up. The timing, magnitude, and distribution of these forces among the four contact patches are at the heart of vehicle dynamics and racecar engineering.

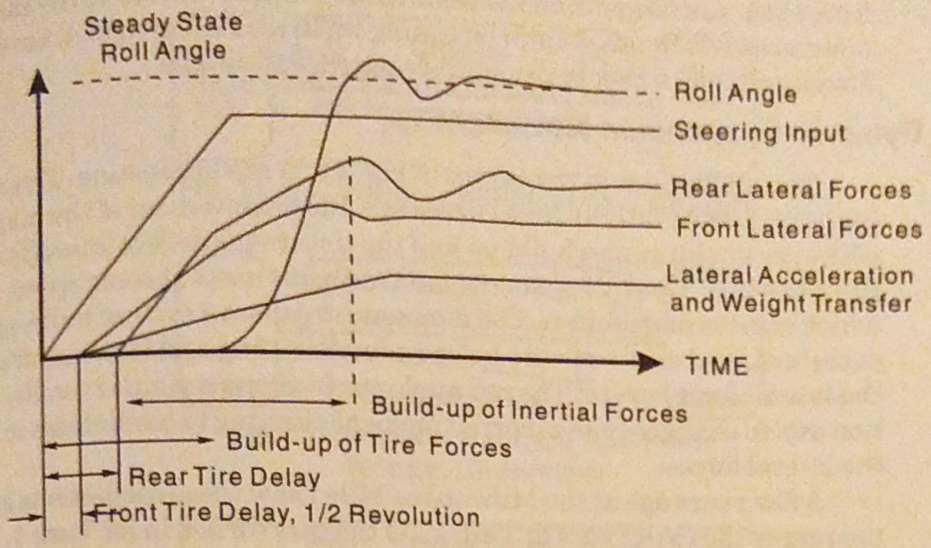

Fig. 11.22 Time Sequence of Cornering Forces and Roll

It takes some time for the driver to turn the steering wheel, and after a steering input the front tire takes about a half of a revolution of the tire to reach the full slip angle demanded by the driver. If the rear tires were not fixed they would rotate as if on casters, and the car would spin out. But the rear tires are fixed and, after some delay of their own, they assume a slip angle sufficient to hold the car in the radius of the turn. (Note that the relative slip angles of the front and rear tires at this point indicate balance—understeer if the front tires go to a bigger slip angle and oversteer if the rear tires need a larger slip angle.) As the front and rear tires take on slip angle, they generate rising lateral forces and feed them into the chassis through the suspension links. These tire forces cause an inertial reaction that is the reason weight transfers from the inside tire contact patches to those on the outside of the turn.

But, as described in the paragraphs above, the center of mass of the chassis (CG) is probably above the roll center, so there is a portion of the inertial force—a roll force—trying to roll the chassis toward the outside of the turn. This roll force also transfers force from the inside tire contact patches to those on the outside, but the build-up of that action occurs over some time due to the resisting force of the springs, dampers, and anti-roll bars. We'll explain that in more detail in the tuning chapter.

The timing depicted in this graph is not exact, but note the time relationships between the various forces. The driver turns the steering wheel through an arc at some speed. The front tires ramp up to a lateral force, oscillate slightly, and settle into a steady state slip angle. The rear tires react similarly with a time delay from the front tires and

forces that are larger than the front tires, because the rear of the car is more massive. In the chapter on tuning we'll calculate weight-transfer forces and take a look at tire contact-patch load details.

Dynamic Suspension Movement

The oscillations in the curves of Fig. 11.22 are interesting. Those in the front/rear lateral force curves are due to movement of the mass of the car as slip angles build up and the tire treads deflect laterally on the sidewalls. These movements indicate some mass at some speed, which creates momentum. The momentum causes a cycle of build-up, overshoot, and over recovery before a final settling and leveling off in the lateral force curves. The roll angle curve shows a similar oscillation due to changes in the inertial moment reacting to oscillations in the lateral forces.

A few years ago at the Milwaukee Mile I saw these oscillations at the rear of the CART cars in Turn 1. As the cars turned in for Turn 1, I could see the rear of some cars move outward, stop, move inward, stop, move outward once more but less noticeably, and then stabilize. I think this movement was roll oscillation and the mass of the rear of the car moving laterally on the tires.

Michael Andretti's car seemed to move more than others, so I asked his engineer, Peter Gibbons, about the phenomenon. Peter told me that, indeed, Michael could feel the movement. He said the severity of the movements depended on how much fuel was on board and the condition of the tires, with maximum movement coming just after a pit stop when the car was full of fuel and had tires giving max grip. Some drivers have the confidence to accept movements of this magnitude and others don't.

Special Case: The Panhard Rod

Not all suspension systems have their wheels sprung independently. Up until the last decade of the 20th century most of our road cars had the rear wheels connected by a solid housing of some sort. NASCAR, Trans-Am, and most stock-based racing organizations require this type of suspension. In this case lateral and longitudinal links transmit forces from the tires to the chassis and provide positive location of the rear axle housing. NASCAR requires a pair of longitudinal links mounted on the chassis forward of the rear axle and a single lateral link known historically as a Panhard rod but more often called a "track bar."

In this type of suspension shown in Fig. 11.23, the point where the Panhard rod intersects the longitudinal centerline of the car determines the roll center. For cars racing on ovals with left-hand turns only, the Panhard rod is mounted to the chassis on the right side and to the axle housing on the left side, putting the rod in tension in left-hand turns.

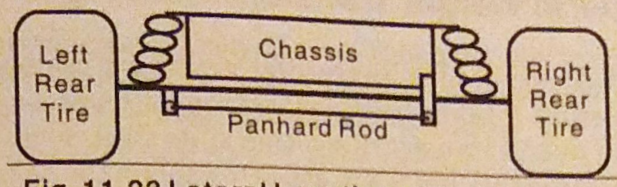

Fig. 11.23 Lateral Location of Axle Housing

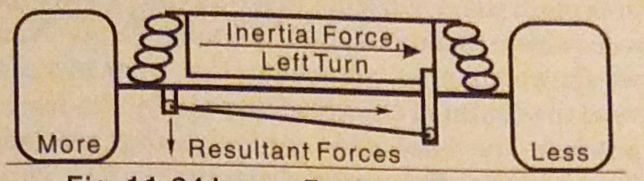

Fig. 11.24 Lower Panhard Rod Pivot, Wedge, Understeer

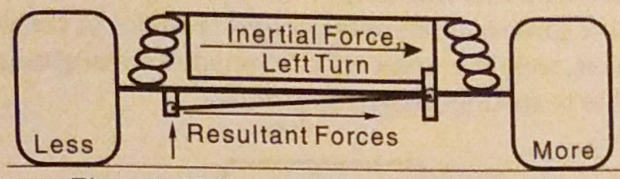

Fig. 11.25 Raise Panhard Rod Pivot, Dewedge, Oversteer

In practice an adjustment screw is incorporated into the chassis mount so the height of that end (right) of the bar is adjustable. With an independent suspension, the height of the roll center determines the direct force/roll distribution of the inertial force caused by tire forces, and a similar situation exists with this type of rear suspension.

Normal adjustments don't change the roll center a lot, but changes to the track-rod angle affect the relative amount of weight transfer across the axle pair of tires. If the Panhard rod is parallel to the axle housing it transmits lateral load only. When the rod angles down from axle to chassis mount (left to right from the rear), the left-rear tire gains some load (wedge). This is an adjustment toward understeer and is shown in Fig. 11.24. The opposite adjustment, the rod angles up toward the right, jacks the left-rear tire up (dewedge), which is an adjustment toward oversteer as in Fig. 11.25.

When the chassis moves vertically on the ride springs, the chassis-mounted end of the Panhard rod moves also. This causes rear-tire load variations into and out of corners. Chassis movements due to banking also move the chassis-mounted end of the rod. For this reason Panhard rod adjustment is used to control jacking forces and therefore balance at mid-corner, where the car has settled into a relatively stable ride height.

Details of Lateral Weight Transfer

Real four-wheel vehicles transfer weight in a complicated manner when cornering. It takes careful measurements and computer software to examine weight transfer in a corner at its most complicated and most accurate detail, but we're going to explain the basic concepts in this section and do some actual approximate calculations. The goal here is to explain these concepts in a way that allows people to understand basic vehicle dynamics and the trade-offs involved.

As we showed in previous schematics, a car in a corner is accelerated toward the center of the arc of its path by tire forces acting at the contact patches. The mass of the car resists that acceleration with an inertial force acting at the center of gravity, the CG. This inertial force generates lateral weight transfer, which we described earlier in this chapter. If we look at this weight transfer in more detail we find it is composed of three components: weight transfer of the vehicle's unsprung mass, weight transfer of the vehicle's sprung mass, and weight transfer due to sprung-mass roll stiffness.

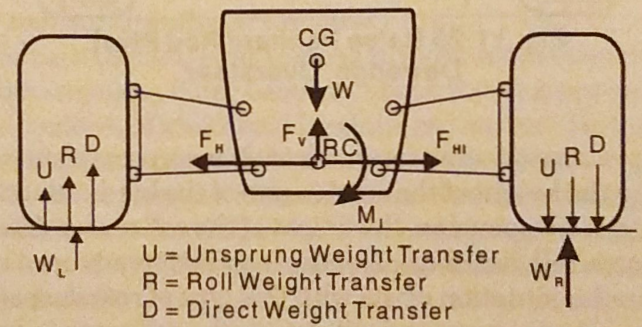

Fig. 11.26 Detail Weight Transfer, Left Turn

Fig. 11.26 shows a two-wheel, rear-end view of a chassis. The tire forces are acting through the RC and are resolved into a horizontal force, F_H, and a vertical force, F_V. F_{HI} is an inertial reaction to F_H acting at the RC. Acting at the CG, the center of gravity of the vehicle, is the weight of the vehicle, W. As you can see, F_V opposes W, raising the car on its springs and earning its name, the jacking force. The moment about the RC, M_I, is the roll moment we created when we moved the inertial force to the RC.

The moment and these forces create lateral weight transfer, which is the sum of three components shown in Fig. 11.26: unsprung weight transfer, direct weight transfer, and roll weight transfer. We'll look at each separately and then do a calculation.

Unsprung Weight Transfer

Most vehicles use some form of springing mechanism to isolate the passengers from road irregularities. This splits the weight of the vehicle into sprung weight—the chassis, engine, and body—and the unsprung weight—the wheels, tires, axles, hubs, brakes, and a portion of the suspension links. In a detailed analysis of weight transfer, the unsprung and sprung portions of weight are handled differently. We'll discuss unsprung weight first.

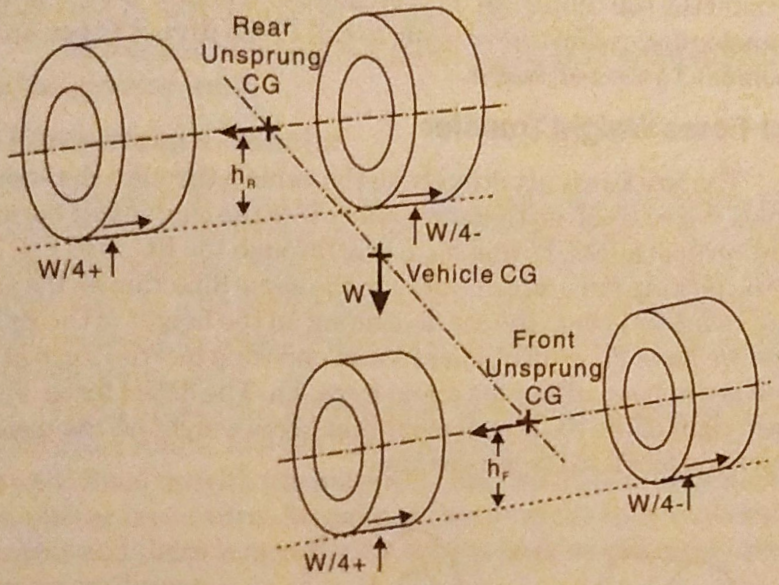

Fig. 11.27 Unsprung Weight Transfer in a Left Turn

In Fig. 11.27 we see the lateral forces generated by the tires, the weight of the car, W, acting at the CG of the vehicle, and the two inertial forces acting at the unsprung CGs, front and rear. The approximate heights of the unsprung CGs, h_F and h_R, are half the diameter of the tires.

Lateral weight transfer from the unsprung weight of each axle can be calculated independently using the same relationship we used before: the fraction of the total weight that is transferred is the lateral acceleration times the CG height of the unsprung weight on that axle divided by the track of that axle.

That's FLT = A x h/t. Multiply times 100 to get percent.

Sprung Weight Transfer: Direct Forces and Roll Forces

Earlier in this chapter we discussed and defined the instantaneous roll center of an axle pair of tires. During that RC discussion we made an engineering approximation, replacing the tire forces with a combination of forces at the RC—an inertial reaction to the tire forces and a moment about the RC. We're going to start there and get a little more accurate and a little more complex.

Our engineering approximation, shown in Fig. 11.21, created two tire forces, F_H and F_V, acting through the roll center, RC, and a moment around the roll center, M_I. F_I is an inertial reaction to F_H. For weight-transfer discussions we're going to call F_I the **direct force** and the moment M_I the **roll force**.

Direct-Force Weight Transfer

The tire forces act directly on the vehicle through the suspension links. We've resolved these tire forces into the equivalent horizontal and vertical forces, F_V and F_H,acting through the RC as in Fig. 11.21. F_V is the jacking force which works in the same direction as the springs and raises or lowers the car depending on the height of the roll center. And we have F_H, which generates an opposing inertial force at the RC that we're now calling the direct force, F_D. The direct force, F_D, times the height of the RC is a moment that takes weight off the inside tire and transfers it to the outside tire.

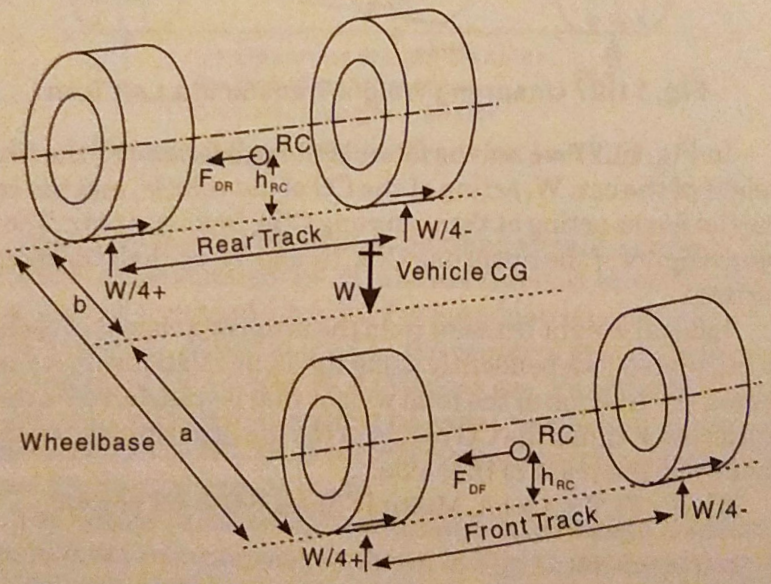

Fig. 11.28 Direct Force Weight Transfer in a Left Turn

Direct forces act instantaneously as tire forces build up with slip angle from the tire contact patch through the suspension links at each axle. We know the car is not spinning in the plane of the road, so these direct forces must be balanced, front to rear. We can't calculate the direct force at each axle, but we can calculate the sum of these forces using the suspended weight of the vehicle and the lateral acceleration of the car. Then we can calculate the direct forces for each axle based on the longitudinal location of the sprung-mass CG within the car's wheelbase.

Referring to Fig. 11.28, the fraction of front direct force transferred = A (b/WB) x front RC height/front track.

The fraction of rear direct force transferred = A x (a/WB) x rear RC height/rear track.

Roll-Force Weight Transfer

As we saw in Fig. 11.22, steering input causes front-tire slip angle, front and rear tire forces, and lateral acceleration of the car, which generates opposing inertial forces in the sprung and unsprung masses of the vehicle. The vehicle's body is mounted on springs and reacts to inertial forces by rotating around some point that we have defined as the roll center, RC.

Think about this! If there were no body roll stiffness the body would just rotate, like the blow-up doll on the wagon in Fig. 11.6, until it's CG lined up with the roll center, and would then stay there as long as the car is in a turn. Actually, if the CG of the body is above the roll center and there is no roll stiffness, the body would rotate even under static conditions.

The springs support the body, providing at least enough static roll stiffness to keep the body upright as in Fig. 11.7. Similarly the springs support the body in a turn, providing roll stiffness in opposition to roll forces. As you might imagine, anti-roll bars, if installed, also add roll stiffness. And dampers add roll stiffness, but they have to be moving. They generate no force at rest.

Roll forces only get to the tire contact patches if there is some resistance to roll. If the car is suspended by springs alone, then the springs on each wheel deflect until enough force builds up to oppose the roll forces. Springs on the outside wheels compress and the ones on the inside expand. Soft springs allow more body roll than stiff springs.

This is important!!! The tire axle pair that has more roll resistance—stiffer springs or bars or dampers—will transfer more of the total roll weight across that pair of tires. And we know now that the load sensitivity of tires dictates that more load generates decreasing increments of grip. That's why when weight transfers in a turn the

stiffer end of the car loses some grip relative to the other end. This phenomenon allows a very sensitive balance adjustment—relative front/rear roll stiffness distribution.

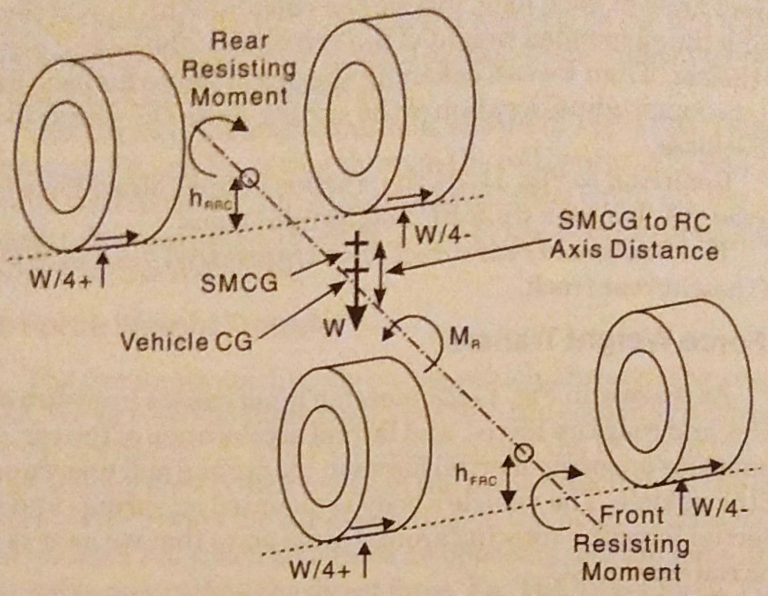

Fig. 11.29 Roll Moment Weight Transfer in a Left Turn

Fig. 11.29 lays out the values we need to calculate the front and rear roll forces. M_R is the total body roll moment proportional to the car's sprung weight, the lateral acceleration, and the distance between the RC and the sprung mass CG, or SMCG in the schematic.

When we calculated the unsprung weight transfer we used the height of the unsprung CG. When we calculated the direct force we used the height of the RC. Now as we calculate the roll force we use the distance between the SMCG and the RC. But we also have a multiplier that takes into account the front/rear roll resistance distribution. Rear roll resistance divided by total roll resistance gives the rear portion (RM/TM), and front roll resistance divided by total roll resistance (FM/TM) is the front portion.

The rear roll force weight transfer fraction is A x (CG-RC) x RM/TM.

The front roll force weight transfer fraction is A x (CG-RC) x FM/TM.

Weight Transfer Calculation

Let's define a simple car and make a weight transfer calculation.
Total weight: 2,000 lb.
CG: 18 in high, 60 in behind front-axle centerline.
Front weight: 800 lb, equal on both tires.
Rear weight: 1,200 lb, equal on both tires.
Wheelbase: 100 in.
Front track: 55 in.
Rear track: 55 in.
Front unsprung weight: 100 lb.
Rear unsprung weight: 200 lb.
Tires are 28 in diameter.
Front roll center: 10 in.
Rear roll center: 10 in.
Front roll stiffness = 60% of total roll stiffness.
Lateral acceleration: 1.25 G to the left.

The **unsprung weight** transfer at each end is the unsprung weight times the Fractional Weight Transfer. FWT = A x h/t.

For the front unsprung weight, FWT = 1.25 G x 14 in (half the tire diameter) / 55 in = 0.318. The front unsprung weight is 100 and 100 lb x 0.318 = 31.8 lb.

The rear unsprung weight uses the same TWT = 0.318. The rear unsprung weight is 200 lb and 200 lb x 0.318 = 63.6 lb.

The **direct-force weight transfer at the front tires** is the suspended mass (2,000 lb minus the front and rear unsprung weight, 300 lb = 1,700 lb) SM x A x b/WB x front RC height/front track = 1,700 lb x 1.25 G x 40/100 x 10/55 = 155 lb.

The **rear direct force transferred** = 1,700 lb x A x (a/WB) x rear RC height/rear track = 1,700 x 1.25 G x 60/100 x 10/55 = 232 lb.

The roll force is proportional to the distance from the suspended-mass CG (SMCG) to the RC so we have to calculate the SMCG height. We know the total weight is 2,000 lb and that CG is 18 in high. We also know the unsprung weight is 300 lb with a CG of half the tire diameter, 14 in. Once again we sum moments, this time around a point on the ground below these CGs. The total weight times its CG has to equal the unsprung weight times its CG plus the sprung weight times its CG:

2,000 lb x 18 in = (300 lb x 14 in) + 1,700 lb x SMCG)

SMCG height = (2,000 lb x 18 in) – (300 lb x 14 in) all divided by 1,700 lb.

SMCG height = 36,000 – 4,200 / 1,700 = 18.7 in.

The **front roll force transferred** = 1,700 lb x 1.25 G x (18.7-10) x 0.6/55 = 202 lb.

The rear roll force transferred = 1,700 lb x 1.25 G x 18.7-10) x 0.4/ 55 = 134 lb.

Now we can get the total front weight transfer by adding the unsprung, direct, and roll weight transfers.

Total front weight transfer = 31.8 + 155 lb + 202 lb = 388.8 lb. We started with 400 lb on each front tire and now there's about 11 lb on the left-front and 789 on the right-front tire.

The total rear weight transfer is 63.6 + 232 + 134 = 429.6 lb. We started with 600 lb on each rear tire so now there's about 170 lb on the left rear and 1030 lb on the right-rear tire.

Roll Angle

The roll angle of the car depends on the roll moment and the roll resistance of the springs, anti-roll bars, and dampers. The total roll force we just calculated is 202 + 134 = 336 lb. If we multiply this times the track (55 in) we get the roll moment: 18,490 lb-in. If our springs generate a roll stiffness of 20,000 lb-in/degree, our roll angle is 18,490/ 20,000 = 0.9 degrees.

We'll look at all this in more detail in the tuning chapter. The next chapter defines some basic suspension geometry variables and how they affect the tires.

"It burbles through the whoop-de-doos."
—feedback from a driver to his engineer.

CHAPTER 12

SUSPENSION GEOMETRY

In this chapter we'll describe the more important concepts involving steering and suspension geometry and how they affect the tires. Our goal here is to make the reader familiar with the major geometry variables leading up to the final chapter, which will describe how to tune the handling of a car.

For someone starting out on their own to design a car there are more geometry details than we're going to address in this book. For that designer there are books and sophisticated software programs that provide detailed analysis of suspension geometry.

Camber Control

One of the tasks we're asking of our suspension links is that they control the attitude of the tire with respect to the chassis and also with respect to the road surface. Negative camber, where the tops of the tires are nearer the center of the car than the bottoms, reduces tire rollover and allows a better contact-patch shape, producing additional lateral force without a large increase in slip angle and tire heating. Most importantly we want a specific amount of negative camber—the most we can get away with—on the loaded tire in the middle of the corners.

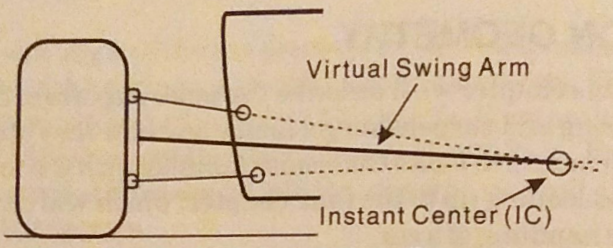

Fig. 12.1 Virtual Swing Arm Construction

One of the suspension trade-offs desirable is minimum change in camber over the range of suspension travel. Fig. 12.1 shows how we can find the instant center (IC) of a set of control arms. The instant center is just that—the instantaneous center of rotation for that linkage. At some specific position, in this case the static position, both the upper and lower control arms can be replaced by a single arm, called the virtual swing arm, whose length is defined by the distance from the outer suspension pivots to the IC.

Fig. 12.2 shows that a longer virtual swing arm causes less camber change for the same wheel movement.

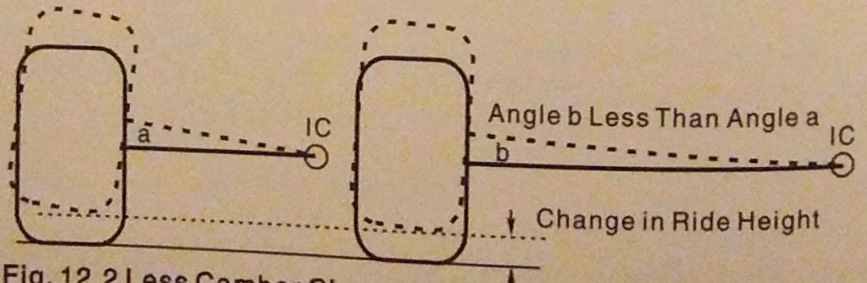

Fig. 12.2 Less Camber Change with a Longer Virtual Swing Arm

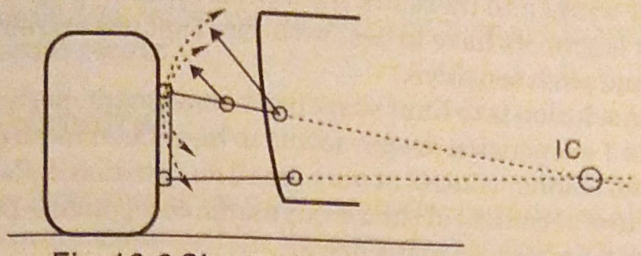

Fig. 12.3 Shorter Upper Arm Increases Camber Change

Fig. 12.3 shows that the length of the upper-control arm has an effect on the amount of camber change with roll or change in ride height. A longer arm generates less camber change for the same suspension movement.

Roll- and Ride-Height Effects

Choosing suspension components and geometries involves a wide range of choices and compromises. Finding an optimum configuration requires analysis of tire/chassis/road interaction, prioritizing requirements, and deciding on trade-offs. With the graphics in Fig. 12.4 and Fig. 12.5 we get an idea of what happens to the tire attitude when the ride height changes and also when the chassis rolls. As mentioned before and again below, restricting suspension movement is a common strategy.

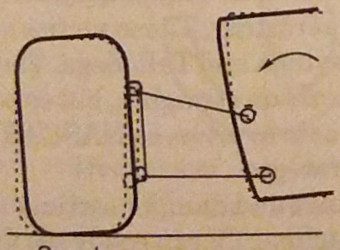

Fig. 12.4 Roll Effects: Scrub and Camber

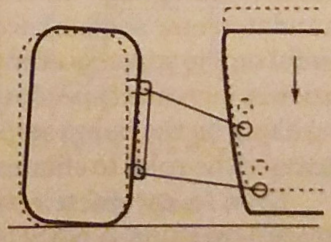

Fig. 12.5 Ride-Height Effects

Aerodynamic Constraints

In the real world of current racecar design, aerodynamic requirements override almost all other trade-offs. Aero components generate maximum downforce at a specific ride height and underwing rake, the front-to-rear increase in ground clearance. The phrase you hear most often is "pitch sensitivity." Since movable aero components are not allowed, rake also controls the angle of attack of airfoils in the front

kingpin axis determines the caster angle and the amount of mechanical trail, the distance between the kingpin axis intersection with the ground and the center of the contact patch. More trail produces a longer moment arm for lateral forces produced in the contact patch and therefore a higher steering force.

Spindle length is the distance from the kingpin axis to the wheel centerline at axle height. With spindle length and kingpin inclination, steering in either direction away from center raises the car. More spindle length and more kingpin inclination causes the car to rise more with steering. Since the weight of the car resists that rise, this is an aid in centering the steering at low speeds. At higher speeds mechanical trail keeps the contact patch behind the kingpin axis, ensuring that tire rolling resistance will produce forces that center the steering.

Caster

Caster angle is similar to kingpin inclination in that it causes the car to rise with steering. While kingpin inclination raises the car with steering in both directions, caster has an opposite effect on the two front wheels, it raises one and lowers the other. If caster is symmetrical, the same on both wheels, steering to the left raises the left wheel and lowers the right. This rolls the car to the right and produces diagonal weight jacking, the left-front/right-rear tires get more weight and the right-front/left-rear tires lose weight. This is an oversteer effect in a left-hand turn.

Caster angle effects camber change with steering. Positive caster, the top pivot leaning backward in side view, produces negative camber on the outside wheel and positive on the inside wheel with steering. The front tires "lean into" the turn, which is generally a favorable characteristic.

Karts and Caster and Tires

Karts exhibit a peculiar characteristic that I think I can finally explain. This book has many pages explaining the load sensitivity of tires—they produce less incremental grip as vertical load increases. This means lateral weight transfer is counter-productive, and racers spend a lot of time and money trying to improve grip by lowering the car's CG.

But karts are quicker through corners with additional weight transfer. I've seen karts with extra weights bolted high on the back of the seat, and racers don't make changes like that unless it makes their vehicle faster. I propose the following explanation.

Karts have a lot of caster and long spindle lengths causing a large amount of diagonal weight jacking as described above. In a left turn, steering and caster pushes the left-front tire down and raises the right-

front. This puts more weight on the left-front/right-rear diagonal and lightens the tires on the other diagonal. The rear axle drives both rear tires equally but the left-rear tire has almost no weight on it due to lateral and diagonal weight transfer.

So the left-front tire is planted with a lot of grip, and the highly-loaded right-rear tire is driving the kart like a model airplane on the end of a string. The kart chassis is flexible so more weight transfer at the rear doesn't unload the right-front tire; it just allows the right-rear tire to drive harder.

Kart tires are also more efficient at handling lateral forces than full-size tires. Eleven-inch diameter kart tires have treads as wide as 7 in. The tread/diameter ratio is about 0.64. A CART tire 28 inches in diameter has a tread about 13 in wide. It would have to be 18 in wide to have the same tread/diameter ratio as a kart tire.

A wide tire is stiffer to lateral loads and the contact patch doesn't deform as much as with a more narrow tire. You can visualize this by thinking of how much stiffer a sheet of 8.5-x-11-in sheet of paper is than a 1-x-11-in ribbon, when both are rolled into a cylinder.

Mechanical Trail

In Chapter 6 we described the self-aligning torque (SAT) in tires caused by the lateral force acting behind the mid-point of the contact patch. The distance from the contact-patch mid-point to the point where the collective lateral force acts is called the pneumatic trail. Mechanical trail is a similar phenomenon caused by suspension geometry. Take a look at the side view in Fig. 12.6. The kingpin axis points forward at the bottom creating mechanical trail, the distance from the kingpin axis intersection with the road surface back to the center of the contact patch.

When the tire produces lateral force, that force acts on the suspension with a moment arm of the mechanical trail plus the pneumatic trail, producing a steering torque the driver has to overcome to maintain the desired steering angle. The SAT is extremely useful because it goes away at high slip angles, telling the driver the adhesion limit is approaching. For that reason mechanical trail should not be large compared with pneumatic trail.

Ackermann Steering Geometry

Almost 200 years ago Rudolf Ackermann patented a steering system that allowed a four-wheeled vehicle to turn a corner smoothly even though the wheel on the outside of the front axle is on a path of larger radius than the inside front wheel. Ackermann geometry results when the steering is done behind the front axle and the steering arms point toward the center of the rear axle.

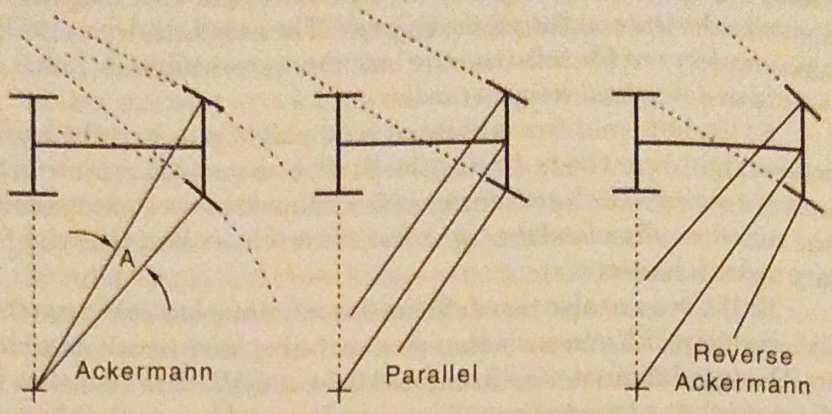

Fig. 12.7 Ackermann Steering Geometry

The schematics in Fig. 12.7 describe the effect of different steering geometries. For a car turning slowly the front tires move in arcs of different radii and need different steering input. The steering mechanism shown is behind the front-axle line. If the steering box is ahead of the axle, the links point forward but still have to point to an intersection ahead of the car the same distance from the front axle as to the rear axle.

Parallel steering geometry turns the tires the same amount and reverse Ackermann turns the outside tire more than the inside tire. Fig. 12.8 shows the action of the links that cause the desired geometry.

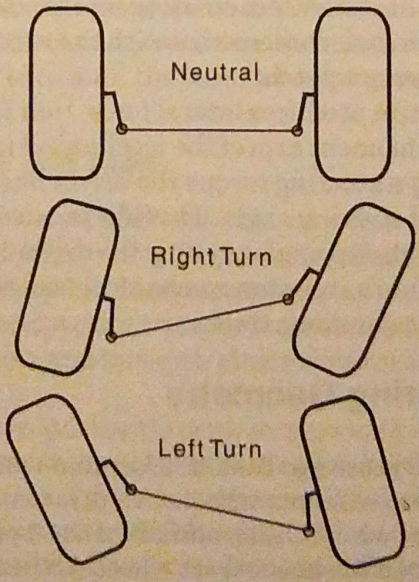

Fig. 12.8 Ackermann Steering Action

Ackermann geometry works well at low cornering speeds when the tires are at small slip angles. The reality of a racecar at speed in a corner is large slip angles, and most of the vertical force is on the outside tires. Complicating this is the dynamic nature of the cornering process. It would be nice to get some cornering force from the inside front tire while it's still got some weight on it, and make sure it's also doing whatever work it can when it's lightly loaded.

Parallel steering or even reverse Ackermann, shown in Fig. 12.9, are used in racing. Choosing steering geometry is another compromise. One of the considerations is the necessity to push the car around in the paddock and on pit lane. Another problem is scrubbing the inside tire in a turn. These practical considerations restrict the use of radical geometries. Steering geometry determines relative slip angles and works in conjunction with static toe, which is described in the next section.

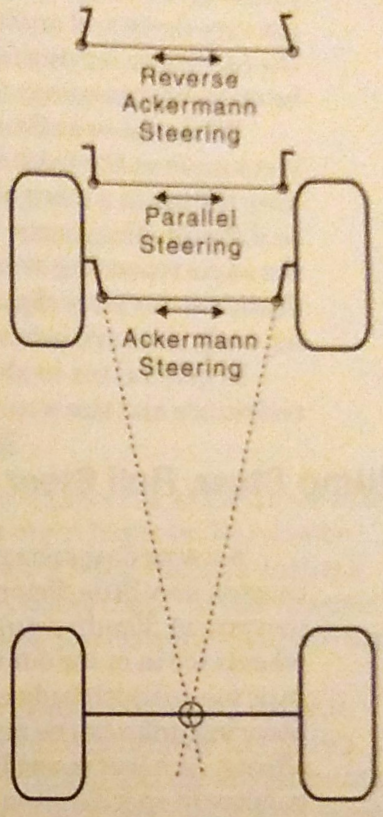

Fig. 12.9 Ackermann Construction

Toe

Once again we're talking about a static setting that has dynamic implications. In early road cars, manufacturing tolerances prevented precise control of steering and suspension movements. More recently rubber bushings in road cars reduced noise but also introduced control errors. But now, with modern materials, precision measurement equipment, on-board data acquisition, and software analysis tools, it's possible to know exactly how suspension components move and interact. In modern times as well as in the olden days, toe, the inward- or outward-pointing attitude of the front wheels, is a useful adjustment.

It seems reasonable that the tires should be pointed straight ahead if the driver wants to go in a straight line. But if you think about it, the tires are slowing the car under braking by pulling backward on the chassis. It there's any compliance in the suspension linkages those

forces could result in tires going to toe-out and the front of the car can get very darty and unstable. We have the same situation at the rear of the car where driving forces push the wheels backward. Toe-out would be unstable here also.

While toe-in at the rear seems to be the consensus, static toe-out is common at the front wheels on racecars. The driver is expected to keep the car in a straight line during braking even though that might be difficult. The reason for toe-out has to do with the tires and follows the same reasoning as in the discussion above about Ackermann. Static toe-out adds slip angle to the inside tire and gets that tire working early in a turn before the weight transfers to the outside tire.

In general toe-in should be kept to a minimum to reduce rolling resistance and tire wear, especially on very high-speed race tracks.

Bump Steer, Roll Steer

Racecar designers position the suspension and steering links so there is very little distortion of steering geometry with suspension movement. Road cars usually have some bump steer— the front wheels toe in or toe out with vertical wheel travel. And roll steer, toe in or toe out with body roll, is another common steering distortion. Steering links can be modified to remove or at least lessen bump steer effects. As a last resort bump can be quantified and used to improve balance in specific situations.

Bump steer can be quantified by moving the suspension while measuring toe. The graph in Fig. 12.10 shows the results of such a test.

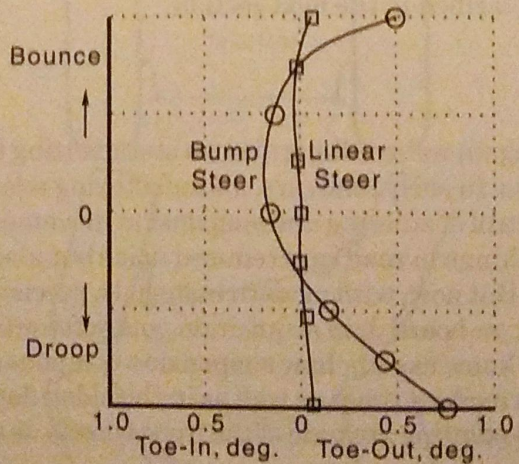

Fig. 12.10 Steering Change with Suspension Movement

Now let's see how to use all these adjustments.

"We cover up our wings and dampers when the car's in the pit lane because I don't want someone to copy our set-up and kill themselves."

—anonymous Indy car engineer.

CHAPTER 13

TUNING FOR GRIP AND BALANCE

Whether you're a professional race engineer or a club racer or an autocross competitor, you're always trying to improve the racecar. And serious fans watch a race team making setup changes during a track session and wonder "Why are they doing that?" In this chapter I hope to describe the basic process of using tire characteristics to tune a car for more grip and better balance.

These are not my original ideas, of course, but reflect current basic procedures used by race engineers and informed club racers. We're not going into the details of how to make specific adjustments. There are how-to books written by people with more hands-on experience than myself. The goal here is to deal with some basic concepts and explain them well enough that people can understand them.

Given a racecar, a set of tires, and a competent driver, the major variables determining lap times are tire traction and the dynamic loading of the tires. The tires produce maximum grip when inflated properly, and are brought into the correct temperature range and loaded at an optimum camber angle.

Some basic racecar design variables—track width, CG height, roll-center heights, and roll stiffness—determine lateral weight transfer. The first two—track width and CG height—might be difficult to change on some cars. Roll stiffness—springs, anti-roll bars, and dampers—are easily adjusted on most racecars. Roll centers might be more difficult to adjust than springs, dampers, and bars, but racers need to understand the effect of RC changes.

Balance, the front/rear distribution of lateral tire forces, depends on tire construction, sizes, and inflation pressure; static front/rear weight distribution; and the front/rear distribution of roll stiffness. When a racecar is balanced all the tires can work near their maximum grip when fully loaded in a corner.

Tuning the Racecar By Levels

It's best to approach tuning the racecar in three levels, optimizing each level before going on to the next. We're going to assume the steering geometry is close to optimum and the car doesn't have any serious roll-steer or bump-steer problems. The first tuning level is the spring rates of the main ride springs, roll-center heights, and the stiffness of the anti-roll bars. This basic level of setup provides the support the car needs to prevent bottoming and also roll resistance, which limits chassis roll due to inertial forces in a turn. We'll provide some rule-of-thumb starting points for spring rates, ARBs, and roll centers.

This is an initial level only, and these same parameters will change as the setup becomes fine-tuned. But this first level should also provide a baseline setup when a racer gets lost after a lot of changes.

The second level, dynamic roll stiffness, can be adjusted using roll-center heights and the dampers. If a car has adjustable aerodynamic components those are the final tuning layer, but we're not going to cover aerodynamics in this book.

If you're off on ride-spring rates you can tweak the anti-roll bars and/or dampers to compensate. But ARBs amplify lateral weight transfer, decreasing available grip. Dampers don't add roll resistance unless they're moving, so they only work at the entrance to a corner (roll) or the exit (deroll). In the middle of the corner you might still have a balance or grip problem, and the shocks can't help because they're not moving.

It's the same with aerodynamics. You can change the rear Gurney flap or the angle of attack of a front wing element to correct balance, but that will work only at speed and the effect is variable with the square of the car's speed. At low speeds you might still have a problem.

So it's best to get things right in the order of more basic to more complicated. If you optimize each layer before going to the next, the car will be more efficient and easier to drive at the limit. Every time you fix a more basic level by fiddling with a more complicated layer the setup window gets smaller, and the car is harder on the tires and harder to drive.

Don't forget the driver, a big part of car performance. The car shouldn't produce any surprises for the driver. If you really get the first two levels, springs, bars, and roll centers, crossed up and use the shocks to correct things, the driver will have a very hard time giving any worthwhile feedback. And what are you going to tweak anyway? You're already off course. Drivers have enough problems reporting simple things. Why complicate the process?

Ride Height

As dynamic as a racecar is there has to be a starting point. The ride height is a measured distance above a level surface between the tires to a specific flat area on the car's chassis. It's useful to determine a front ride height between the front wheels and a rear ride height between the rear wheels. Spots marked on the vehicle centerline can do double duty in making other measurements easier.

A specific ride height can be a useful point of zero adjustment a racer can always go back to and repeat other basic measurements such as toe and corner weights.

Static Weight Distribution

A low CG generates less weight transfer in a corner, allowing the tires to generate more grip. With a lower CG, the axle pairs of tires will be more equally loaded when weight transfers in a corner. A car racing on ovals can improve grip by putting as much weight as possible on the inside tires—up to the limit allowed by the rules.

Front/rear weight distribution is usually determined by the weight of the large components such as the engine, transmission and rear-end housing. If the rules allow it, a racecar designer can remove weight from as many components as possible and replace that weight with ballast that can be moved on the car as needed.

In some race series current rules are limiting front-wing configurations to decrease aero downforce. The rear wings have to be trimmed back to maintain an aero balance. Since the tires are working against the weight distribution of the car, ballast can be moved toward the end of the car that's generating more aero downforce.

I'm told most Formula 1 cars these days have around 200 lb of tungsten ballast mounted low in the chassis. The cars are designed so the ballast is easily moved around for balance adjustments. CART cars adjust F/R weight distribution and wheelbase length by mounting different suspension links that place the wheels further forward or rearward depending on the weight distribution desired.

Moment of Inertia

We introduced the concept of inertia in Chapter 11, and explained lateral and longitudinal weight transfer as inertial reactions to acceleration of the car. This same phenomenon applies to the angular rotation of a car during cornering. The moment of inertia of a body is proportional to the body's mass and the square of the distance of the mass from the center of rotation. So a heavier body is more difficult to get spinning, as is a body with its weight further from the center of

rotation. A big rock sitting in the middle of a turntable is easier to spin than two smaller rocks with the same total weight placed 10 feet apart on the same turntable.

Moment of inertia applies to cars because vehicles need to rotate to negotiate turns. Tires supply the force needed to turn a car, and they have to work less if the car has a low moment of inertia. I've been told that some F1 teams move ballast to the ends of the cars to better heat the tires during qualifying, and then move the ballast back toward the middle of the wheelbase for more efficient cornering during a race.

Corner Weights

For road-course cars there should be near-equal weight on each of the two front tires and the same at the rear. This is simple on some racecars but might be difficult with street cars used in autocross or spec road-racing classes. If the rules allow movement of the battery, take advantage of that.

If you have to make a choice between equal weight on the front tires or equal weight on the rear tires, choose the front. This will result in better braking and steering stability.

Spring Rate, Wheel Rate, Tire Rate

Every spring has a spring rate, the force required to deflect the spring some unit of length, usually one inch. A spring that compresses 1 in with a force of 100 lb has a spring rate of 100 lb/in. In real-world suspension designs, however, 1 in of wheel movement seldom results in 1 in of spring movement. There is almost always a motion ratio between the wheel and the spring.

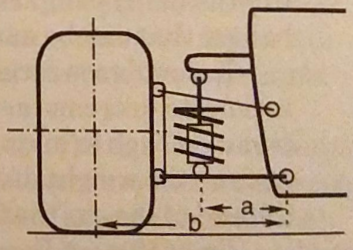

Fig. 13.1 Motion Ratio

Motion ratio is usually defined as the amount of spring movement for a given wheel movement. In Fig. 13.1, distance "a" is about half of distance "b" so the spring moves about half as far as the wheel, giving us a motion ratio, a/b, of approximately 0.5. This motion ratio describes the relative motion of the spring with wheel movement, but also determines the mechanical advantage of the spring. With a motion ratio of 0.5, the wheel rate, the force needed at the wheel to move the wheel through some distance, is proportional to the square of the motion ratio. So a spring with a 100 lb/in spring rate mounted with a motion ratio of 0.5 would produce a wheel rate of 0.5 times 0.5 times 100 lb/in = 25 lb/in.

Heavy cars need higher spring rates at the wheels to support the car and prevent bottoming. Softer springs with a larger motion ratio would work just as well, but you'd need to adjust damping levels. More damping in bump helps the softer springs support the car, but softer springs store less energy for the same bump displacement, needing less rebound damping.

The static spring rate of a tire, the tire rate, depends on the tire design and the inflation pressure. Racers buying tires can sometimes get tire rate information from their tire retailer or the tire manufacturer. Tire rates can be measured by adding load to the wheel—not the tire—and measuring tire deflection-the change in height of the wheel or the hub. The applied load in pounds divided by the tire deflection in inches gives the tire rate in lb/in.

We presented spring-rate tire data in Chapter 10 but noted that a tire's rolling radius is determined by forward speed and lateral force as well as the static spring rate of the tire. Actual tire deflections, vertical, longitudinal, or lateral, are highly dynamic and difficult to measure, much less calculate. Forces on the rear tires of most cars are much higher than those on the front tires, so deflections at the rear are larger. Depending on tire design variables, spring rates, and suspension motion ratios, a 1 psi change in tire pressure can result in a 50 to 60 lb change in wheel rates. We'll have more on that subject later in the chapter.

The only way to produce good data on tire and suspension deflection under dynamic conditions is with a properly instrumented racecar. A data acquisition system reading suspension-mounted position sensors as well as a chassis-mounted laser ride-height sensor can provide good information.

One racer I know fitted a laser on his car and generated some interesting data. His car is a 2,700-lb car with 400 lb/in spring rates and 750 lb/in tire rates. He calculated a dynamic ride height of 0.30 in under a specific set of conditions. But measurements on the racetrack under similar conditions produced a laser ride height reading of 0.50 in. That's enough to make a difference, especially with a ground-effects car.

Bell Cranks and Third Springs

If 1 in of wheel movement compresses a 100 lb/in spring 0.5 in, then the motion ratio is 0.50, and the wheel rate is 25 lb/in. For a coil-over spring/damper arrangement the coil spring and damper are mounted concentrically, and the damper moves exactly as does the spring. Some suspension systems employ adjustable motion ratios that amplify spring and damper movement for better damping with small suspension movements. A damper is more sensitive to adjustment when it's moving more fluid.

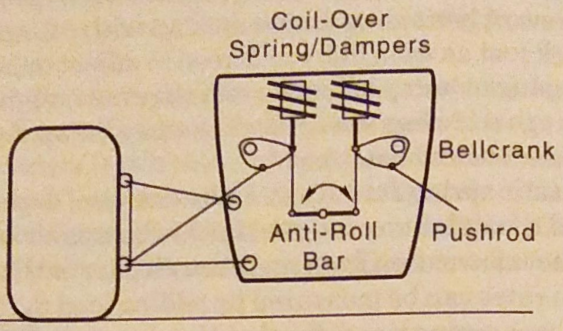

Fig. 13.2 Pushrod and Bellcrank Suspension

Many current racecars have a centrally-mounted coil-over spring/damper unit with a pushrod from the wheel operating on the coil-over unit through a bell crank as shown in Fig. 13.2. This system provides a compact, highly-adjustable, easily-maintainable mechanism. An extra pair of links can operate a torsion spring acting as an anti-roll bar. The angle of the pushrod determines a large part of the motion ratio.

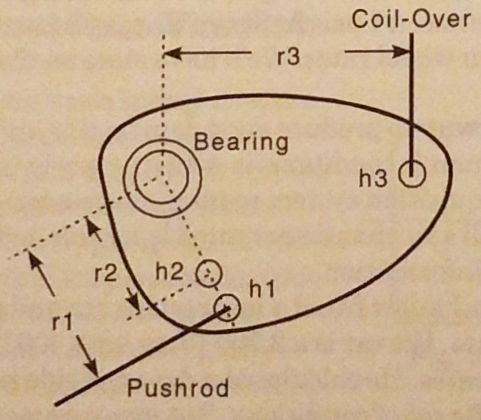

Fig. 13.3 Adjustable Motion Ratios with a Bellcrank

If these bell cranks have several mounting positions for the links, as shown in Fig. 13.3, motion ratios are easily changed. Changing the pushrod mounting from hole "h1" to hole "h2" increases the motion ratio, causing more coilover motion for a given pushrod movement. The ratios of the input and output radii determine the motion ratio of the bellcrank. Since the input and output radii change with bellcrank movement, rising-rate or decreasing-rate spring characteristics are possible. Additional holes in the bellcrank can provide separately adjustable motion ratios for the anti-roll bar linkage.

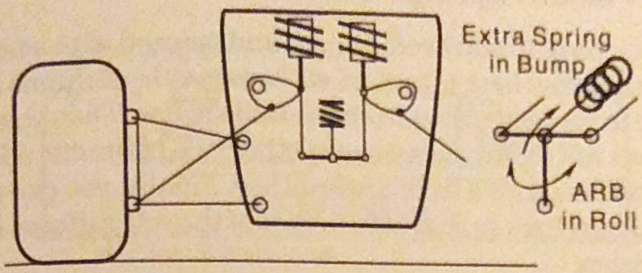

Fig. 13.4 Third Spring Added for Aero Forces

This same suspension system can also provide a solution to the problem of suspension deflection by aerodynamic forces. If the springs in the normal coil-over system had to support the thousands of pounds generated by wings and ground-effects underwings, they would have to be much more stiff than would be optimum in slow-speed corners. The solution is a "third spring" as shown in Fig. 13.4. The linkage still operates the anti-roll bar, and the coil-over spring/damper system works the same at low speeds, but the third spring comes into play at higher speeds as aero forces deflect the main springs.

Third-spring systems in the front and rear suspension work really well on a road course that has high-speed straights as well as slow corners. The third spring doesn't engage at low speeds, so softer ride springs provide good grip in slow corners.

Where to Start with the Basic Setup

Working at the most basic level, springs and bars, requires the removal of wings and any other adjustable aerodynamic device. For all cars the low-speed adjustment on the shocks should be set as soft as possible. We'll assume the car has no severe bump-steer or roll-steer characteristics. Take out any weird toe-in/out settings, front and rear. You want the tires pointed as straight ahead as possible, but don't ignore the manufacturer's recommended settings. I don't want to gloss over bump- and roll-steer. Measuring these characteristics and adjusting for them are critical processes and need to be done carefully in the shop before testing begins.

There are a lot of trade-offs in the tuning process. You start somewhere and work toward a combination that gives better results—a lower lap time.

Starting Points—Springs and Bars

You have to start somewhere and proceed with some plan. The plan suggested here is to start with some rule-of-thumb spring rates for the front suspension from the table below. Then you can calculate the front roll stiffness and use another rule of thumb, adding 10-20% to that stiffness with a front anti-roll bar. Finally, you can choose rear springs and bars so that 50% to 65% of the roll stiffness is on the front suspension.

Identify what kind of car you have and measure the static weight on each corner, at each tire contact patch. The numbers below are the approximate ratio of wheel rate to measured corner weight for a front wheel. You can see these ratios get bigger on cars with more downforce. Downforce requires higher spring rates to keep the car from bottoming on the straights. Depending on the speed and bumpiness of a track, you can adjust spring rates up or down from these numbers. Of course ride height can also be changed to cure bottoming.

Table 13-1: Starting Spring-Rate/Corner-Weight Ratios

Car Type	Wheel Rate/Corner Weight
Formula Ford	1-1.1
Trans-Am	1.2-1.3
Formula 2000	1.6
Formula Atlantic	1.9
D Sports Racer	1.7
ALMS LMP	2.0-2.2
CART/IRL	2.3-2.4

For example, if you have a small, non-aero formula car that has 300 lb on each of the front contact patches, you could start out with 300 lb/in wheel rates at that end. Knowing the motion ratios allows you to use this recommended wheel rate to pick an actual spring rate. Now that you have the front spring rates we can estimate the front roll stiffness and size the front ARB.

Sizing Anti-Roll Bars

Sizing an anti-roll bar can be simplified by choosing to add 10 or 20 percent to the roll stiffness of the springs selected by the rules of thumb above. We need to figure out the amount of roll stiffness contributed by our spring choice before we can size the ARB. Fig. 13.5 presents a schematic of a solid-axle suspension with a roll angle due to inertial forces in a corner. Both springs resist roll, and each spring deflects about the same amount, with one expanding as the other contracts.

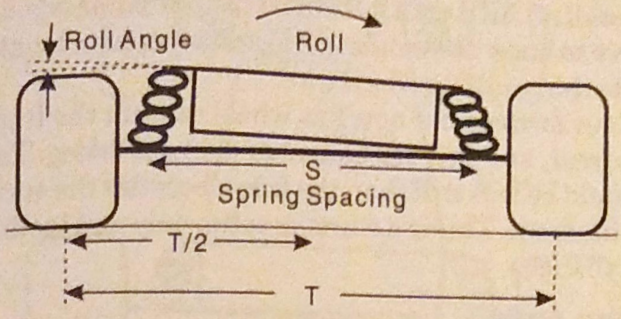

Fig. 13.5 Roll Stiffness Calculation

We can make our calculation using spring rate and spring spacing, but the motion ratio adds complications. We'll use wheel rates, the spring rate at the wheel, which includes the effects of motion ratio. Using wheel rates lets us explain a method that will work for all types of suspensions.

A moment is a force times a distance, also called a moment arm. The roll-resisting moment in this case is the force needed to roll the chassis through some angle times the distance from the spring to the center of rotation. We'll calculate the distance the springs move, and that will give us the spring force. That force times the moment arm gives us the roll-resisting moment.

For a roll angle of 1 degree, spring movement is the sin of 1 deg times the distance from the spring to the point of rotation. If we were dealing with actual spring rates we would use the spring spacing, S, and S/2 would be the distance. But we're dealing with wheel rates, so that distance is half the track, shown as T/2 in the schematic.

For 1 degree of roll the wheel moves a distance with respect to the chassis of T/2 times the sin of 1 degree = 0.01745. This number is the reciprocal of 57 so we can divide T/2 by 57 and get the same result. The amount of movement times the wheel rate, K_W, is the roll-stiffness contribution of one of the two springs supporting the chassis. The moment arm of the wheel rate is also T/2. So the roll resistance of one wheel is $T/2 \times T/2 \times 1/57 \times K_W = T^2/4 \times 1/57 \times K_W$. Multiplying times two for the roll resistance of both springs makes $T^2/4$ become $T^2/2$, so:

Roll resistance per degree of roll = $T^2/114 \times K_W$.

If we use lb/in for wheel rate and inches for the track, the units are lb-in/deg.

From our formula car example above we can calculate the roll resistance of the 300-lb wheel rate on the front wheels. If we say the front track is 60 in, then the roll stiffness for one degree of roll is 60 in times 60 in / 114 times 300 lb/in = 9,474 lb-in/deg. Every additional degree of roll will produce the same amount of additional resistance.

If we want to add an anti-roll bar with 20% of that roll stiffness we'd install an ARB with a stiffness of approximately 2,500 in-lb/deg. You have to know the motion ratio and lever-arm length of the ARB to calculate the resulting wheel rate.

So our formula car now has wheel rates at the front of 300 lb, 250 lb at the rear, and anti-roll bars near 2,500 in-lb/deg. The ARB at the rear should be less stiff than the front, because the springs aren't as stiff as the front. This is a starting setup only and testing will surely dictate changes.

Suspension Antis

These geometries—anti-squat, -dive, and –lift—use inertial forces to limit suspension movements and were described in Chapter 11. Keep these geometries in the zero to 20% range as a starting point. You just don't want to worry about any force that changes ride height when starting the tuning process.

Diagonal Weight Transfer: Wedge

Anyone watching a NASCAR Winston Cup race on TV sees a lot of adjustments going on during pit stops. That race series is extremely competitive, and the cars are highly developed for their type of tracks within a very restrictive set of rules that includes a requirement that all the teams mount exactly the same tires made by Goodyear Tire & Rubber Co. The teams are constantly adjusting the cars, looking for the best balance and chasing changes in track conditions during a race. The TV viewer sees a crewman put a wrench into a hole in the rear window and crank one way or the other. Then the announcers talk about "wedge" or moving the "track bar" up or down. We explained the track bar (Panhard rod) adjustment in the chapter on vehicle dynamics.

"Wedge," also called "diagonal weight jacking," is a way to use a car's static weight distribution to adjust dynamic balance. The most obvious adjustment of wedge comes during a pit stop, when one of the crew members sticks a ratchet wrench with a long extension into a hole at the left side of the rear window. That wrench is turning a bolt that moves the top of that spring perch up or down. It's a normal right-hand thread, so if the guy turns it clockwise, he's moving the spring down, compressing the spring at the left rear corner. This puts more force on the tire at that corner and also on the tire at the diagonal corner, the right front. If he turns the wrench counterclockwise the spring perch moves up putting more static weight on the other diagonal pair of tires, the right rear and left front.

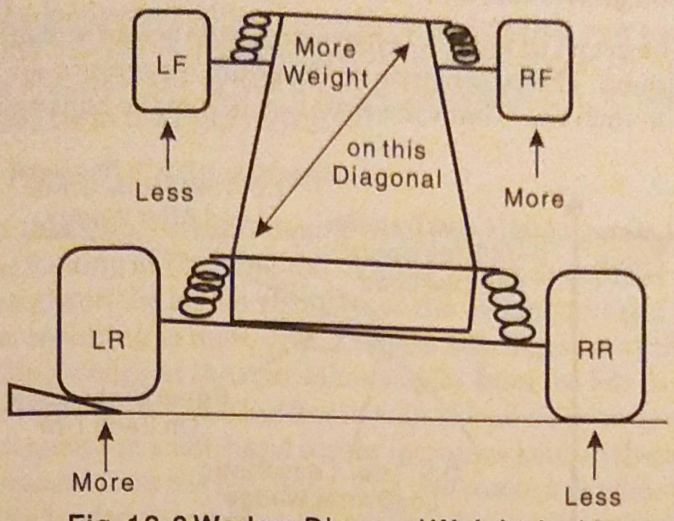

Fig. 13.6 Wedge: Diagonal Weight Jacking

Here's a way to visualize what's happening. This drawing in Fig. 13.6 presents a sprung mass on four wheels, a simple car. A wedge is pushed under the left-rear (LR) tire. The wedge has the same effect as cranking down on the spring perch; it raises the car at that corner, slightly compresses the springs at the left-rear and right-front wheels, and extends the springs at the left-front and right-rear.

Springs produce forces depending on their length. The left-rear and right-front springs are now compressed compared to their length before the adjustment, so there is more force going to the ground at the left-rear and the right-front tires. But the total weight on all four tires is still the total weight of the car, so more static weight on the left-rear/right-front diagonal means less weight on the right-rear and left-front tires.

If you're having trouble visualizing this, it took me a while to figure it out, think about a four-legged kitchen table. If you push a wedge of wood under one leg, that leg rises and the table teeters on that leg and the one on a diagonal from it. If you balance the table on those two legs, the other two are up clear of the floor.

Now think of the legs as having springs in them. All these springs are the same spring rate. If you push the wedge under one of the legs, the spring in that leg will compress as will the one on the diagonal. The legs on the other diagonal were up in the air without springs, but now the ends stay on the ground. It takes a force to compress a spring, so those springs that got longer are producing less force, and the ones that compressed are generating more force. It's the same with the car.

Using Wedge to Adjust Balance

The graph in Fig. 13.7 shows tire loads before and after a wedge adjustment. The larger circle on the graph represents equal static loads on each tire. That's the situation before the adjustment.

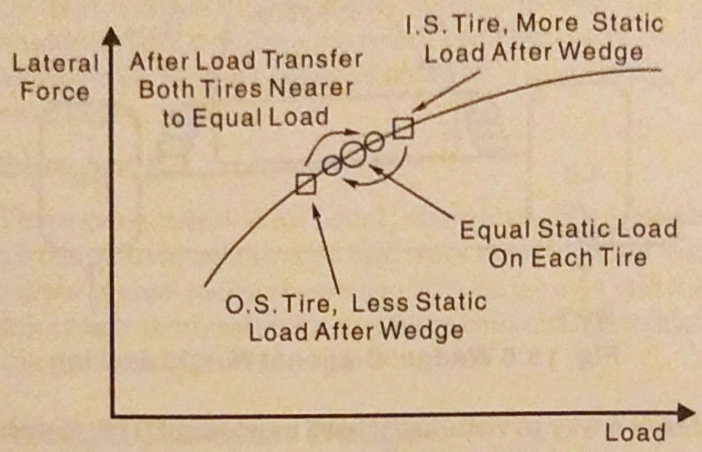

Fig. 13.7 Dynamic Load Transfer With Wedge

Let's say the car is oversteering—the rear is sliding out in the corners. At a pit stop a crewman puts a wrench in the hole at the left rear and cranks it clockwise. That screws down the top spring perch, compressing the left-rear spring. The adjustment jacks up that corner a small amount.

When the left rear rises it takes on some extra static weight and adds some weight to its diagonal, the right front. But the car weighs the same, so there is now less weight on the left-front and right-rear tires.

Take another look at Fig. 13.7. Statically the wedge adjustment has added some load to the inside-rear tire represented by the square moving up the curve. And that same adjustment took some load off the outside tire, moving that square down the curve.

A Static Adjustment with Dynamic Results

These adjustments don't do anything if the car is just sitting still in the pit lane. But we said the car was oversteering in the corner—the rear end was sliding out. More grip at the rear would help that situation. If we take the adjusted car (more wedge) back out on track and into a corner at speed, inertial forces transfer weight from the inside to the outside. But before the turn, the car had more weight on the inside rear tire and less on the outside tire. And when the weight transfers in the turn, it will still have more on the left-rear tire and less on the right-rear tire than it did before the adjustment.

The contact patches are now loaded more evenly in the turn, and due to the load sensitivity of tires, the rear-tire pair now has more grip than it did before the wedge adjustment. More grip at the rear should cure the oversteer the driver was complaining about. At least the adjustment is in the right direction.

A Doubly Powerful Adjustment

But this adjustment is doubly powerful, because it changes the dynamic loading at the front too. Adding wedge at the rear put more static weight on the inside-rear tire, so the dynamic weight transfer was less, resulting in more grip. The opposite happens at the front.

Adding wedge at the rear takes weight from the left-front and puts it on the right-front. Starting from unequal load distribution, dynamic weight transfer in a left-hand corner increases load on the right-front and decreases it on the left-front. The two contact patches are more unequally loaded than before the wedge adjustment, so the total grip of the pair of tires on that axle is less.

That's why wedge, or any action that changes diagonal weight distribution, is such a powerful tool to adjust balance. A small adjustment on one axle pair affects the other axle pair in the opposite direction.

Cockpit-Adjustable Wedge

Contact-patch force distribution among the four tires is such a powerful balance adjustment that only a few pounds can make a critical difference. Open-wheel cars racing on ovals routinely include cockpit-adjustable wedge so the driver can make small balance corrections during a race to correct for fuel usage or changing track conditions.

Here's how they do it. A knob on the dash is attached to a screw that moves a piston in a cylinder, and that forces hydraulic fluid into another piston at a spring perch, usually the one in the left-front suspension. Turn the knob to the right and fluid moves into the spring perch, forcing it down and adding weight to that corner, an adjustment away from understeer and toward oversteer. Turn the knob the other way and the adjustment increases understeer. A useful adjustment used skillfully can win races.

There's a reason why a weight jacker is usually, but not always, installed on the left-front spring perch. Stuff happens and if this hydraulic system fails, it lets the left-front down, which is an adjustment toward understeer and away from oversteer—a more dangerous condition.

Wedge Summary

Adding wedge is defined as adding more static weight on the inside-rear tire. This adjustment is an adjustment away from oversteer and toward understeer. If the front suspension has more roll resistance than the rear, the car wedges itself more as it corners harder, and it will tend to understeer more (or oversteer less) as corner speeds increase.

De-wedging is defined as more static weight on the outside-rear tire, causing more oversteer and less understeer. If the rear has more roll resistance than the front, the car de-wedges itself more as it corners harder, and it will tend to oversteer more (or understeer less) with increased corner speeds. We'll further explain roll resistance later in this chapter.

We now know that the axle-pair of tires that has more equal contact-patch forces when loaded in a corner generates more lateral force. So wedge and de-wedge will cause increased cornering force on the end with added static weight on the inside tire. The end with more static weight on the outside tire will have less cornering force.

Wedge with Tire Pressures

Tires are springs too, and diagonal tire spring-rate changes can adjust balance the same as ride-spring rates or anti-roll bars. During a race there are very few adjustments that can be made to the car. Aerodynamic adjustments such as front-wing angle of attack and rear-wing Gurney flap affect the car at higher speeds because they are proportional to the square of air speed. Tire-pressure changes allow an easy but effective way to adjust the basic balance of racecars during pit stops. Pressure-adjusted tires go on the car at a pit stop and, hopefully, the car is better balanced when the tires come up to the operating temperature and pressure.

Continuing to talk about turning left, more pressure in the right-front tire raises the spring rate of that tire, adding wedge. This puts more static weight on that tire and its diagonal, the left-rear. As a result, when weight transfers in a turn the front-tire contact patches are less evenly loaded, losing some grip, and the rears are more equally loaded, gaining some grip.

As we know now, a tire is a lightly-damped spring in series with a car's main springs and dampers. To calculate the total spring rate of two springs mounted in series we use the relationship: $1/K_{total} = 1/K_w + 1/K_t$. We take the inverse of the spring rates at the wheel, K_w, and the tire, K_t, and add them together to find the inverse of the total spring rate.

Table 13.2: Wheel, Tire, Total Spring Rates, lb/in

Tire Rate lb/in	Wheel Rate lb/in	Total Rate lb/in	Total/Tire %	Plus 1 psi lb/in
1,000	300	231	23	2.6
1,000	500	333	33	5.4
1,000	1,000	500	50	12.2
1,000	1,500	600	60	17.7
1,000	2,000	667	67	21.9
1,000	3,000	750	75	27.8

Table 13.2 presents calculated total spring rates for various wheel rates acting in series with a 1,000 lb/in tire. The Total/Tire column shows the total wheel rate as a percentage of the tire rate. The last column shows the approximate effect on the total wheel rate of adding 1 psi to the inflation pressure. In that case the estimated tire spring rate is 1,050 lb/in. You can see that extra 1 psi doesn't make much difference until the wheel rate number gets close to the tire rate.

Using tire pressure as a balance adjustment is complicated because you have to know how much pressure the tire will gain when it comes up to temperature during use. And your pressure adjustment will probably change the amount of pressure gain on the track. This is where keeping good records pays off.

The change in contact-patch area with inflation pressure is another complication. Lowering tire pressures increases contact-patch area, increasing grip, but lower pressure also decreases tension in the cords that are holding the tire together, resulting in increased tire deformation and heat generation.

For a given set of conditions a lower inflation pressure might put more rubber on the ground and work the tire harder, raising the rubber operating temperature into a range closer to optimum. But that lower pressure might also bring the tire carcass closure to fatigue failure. It's just a fact that sometimes the optimum inflation pressure for a tire compound will be too low for that tire's construction. Lower inflation pressures might give you quicker lap times right up until the tire blows up.

Dynamic Tire Loading

When a car is in a turn, lateral forces from the tires are accelerating the car toward the center of the arc of the car's path. That acceleration causes an opposing inertial force at the car's center of mass, the CG. The tire forces are acting at ground level and the inertial forces at the CG. This creates a moment that changes contact-patch loads from what they were when the car was sitting still. The car

weighs the same but more of that weight is on the tires on the outside of the turn than when the car was static. The inside tires lose the same amount of load that the outside tires gain.

The need to allow the wheels to move with road irregularities dictates a suspension with links and springs between the wheel and the chassis, and this complicates the details of dynamic tire loading. So we make some engineering assumptions about the links and tire forces and separate load changes into three categories: unsprung, direct sprung, and roll sprung.

In the chapter on vehicle dynamics we explained roll centers, and how to roughly calculate the three components of lateral weight transfer: unsprung weight transfer, direct weight transfer, and roll weight transfer. Unsprung weight transfer is easy; it's proportional to the lateral acceleration, the weight of the unsprung components, and the CG height of those components. Unsprung weight transfer is inversely proportional to the track width at that end of the car.

Direct weight transfer is proportional to the lateral acceleration and the weight of the suspended components and is also inversely proportional to the track. But the direct force acts through the roll center, so it's proportional to roll center height. And this total force for the car's suspended mass has to be proportioned front/rear according to the longitudinal location of the CG of the car vs. the wheelbase.

Roll weight transfer is also proportional to the lateral acceleration and the weight of the suspended parts of the car. But, since the moment arm of the roll moment is the distance between the suspended mass CG and the RC, roll force is also proportional to this distance. And, since the chassis would roll freely without some resistance, the front/rear distribution of roll force depends on the front/rear roll resistance of the springs, anti-roll bars, and dampers, if the dampers are moving. Let's try to explain that a little better.

Roll Resistance

Let me describe an example of roll resistance. Say you're sitting in the middle of the back seat of a big road car. The driver turns sharply left, and you would fall to the right if you didn't put out your right hand and stop yourself. That's roll resistance. The lateral acceleration of the car toward the center of the arc of the turn transfers that same acceleration through the seat to your butt, and your seat/butt interface becomes your roll center. Even though you're seated, your CG is above your roll center, and the inertial force of your body reacting to the car's lateral acceleration tries to roll your body about its roll center.

Let's say you're holding a coil spring in your right hand when the driver begins the turn. You quickly stick out your right hand and place the end of the spring against the right door panel. The spring rate of that spring now controls how your body moves as it rolls. As the

spring compresses, force builds up until the spring exerts enough force to stop your body from rolling. Your body will roll through some angle until the spring forces build up and stop the roll. That's exactly what happens with a car!

The force on your hand is analogous to the force on the tire patch. If you have a high-spring-rate spring in your hand, roll-resisting force builds quickly with little roll. A car stiff in roll will quickly put a large force on the outside tire patches. And didn't we say that tires loose grip with an incremental increase in tire-patch forces? That's why a stiffer spring or a stiffer anti-roll bar can decreases grip across an axle pair of tires.

Roll Resistance Distribution

Just as important as the absolute roll resistance is the relative amount of roll resistance of the front suspension vs. the rear suspension. If the chassis is rigid, it rolls the same amount front and rear. Of course not all vehicle chassis are that rigid, and lack of torsional rigidity is one reason why some racecar designs are better than others. When a racecar doesn't respond consistently or linearly to front/rear roll resistance changes, poor torsional rigidity is the first suspect.

Adding roll resistance in the front suspension causes the car to roll through a smaller angle. The rear springs and/or ARBs now deflect a smaller amount, causing less load transfer across that axle pair of tires. The front pair transfers more weight and the rear less, an adjustment toward understeer. So we see that roll resistance adjustments are double acting just like wedge adjustments.

We're finding there are a bunch of ways to increase roll resistance on an axle: stiffer ride springs, stiffer ABR, higher roll center, or more tire pressure. Front/rear roll resistance distribution contributes to balance. Increased incremental roll resistance at the front tends toward understeer; at the rear toward oversteer.

Roll Resistance Trade-Offs

As we described in the chapter on vehicle dynamics, suspension-link geometry determines roll center (RC) location, which can be above the CG, below the ground, or out past the tires. The importance of the RC is it determines the split between the direct and jacking forces and the roll moment. A high RC has a short moment arm for the inertial force opposing the tire forces, so the roll moment is small. But to get that RC high, the suspension link geometry creates a bigger jacking force.

An RC at the same height as the car's center of gravity (CG) creates no roll moment but a lot of jacking force. If RC is higher than the CG, roll forces reverse, the body/chassis rolls into the turn, and jacking forces get even bigger.

Going the other direction, a low RC creates a big roll moment but less jacking force. If the RC is below ground level, jacking forces are negative—the car squats at that end when it turns.

The distance from the RC to the suspended-mass CG, the amount of suspended mass, and the lateral acceleration determine the roll force. The springs and bars have to resist this force and maintain a reasonable body-roll angle. The combined spring rates of the springs and bars determine the amount of roll—the chassis rolls until these forces build up to match the roll force. The rate of roll is controlled by the low-speed damper settings. The combination of forces generated by springs/bars/dampers controls the amount and timing of the weight on each tire patch during cornering.

We want our car to go where it's steered with a predictable, stable attitude. Generally that describes understeer rather than oversteer, so we want the static roll stiffness due to springs and bars to be biased toward the front of the car, close to 55%. This number is good for sports racers, Trans-Am cars, and formula cars on a road course. Oval tracks may need as much as 65% to the front. This assumes that the roll centers are reasonably located for the weight of the car, CG, etc., etc. The compromise reached by a combination of springs, ARBs, and RC locations is extremely important and cannot be completely determined by analysis. Driver/engineer experience and track testing count for a lot.

Geometric Stiffness

We've mentioned that roll center heights also affect roll stiffness. You can think of roll center height as anti-roll, similar to anti-squat or anti-dive. A low roll center means a large roll moment and small direct and jacking forces. To maintain a small roll angle during cornering this type of setup requires stiff ride springs or heavy ARBs. Higher roll centers create less roll force and more direct forces, so softer ride springs and smaller anti-roll bars can still maintain small roll angles. Conversely low RCs can generate roll even with stiff springs and bars. In the final section of this chapter we'll show some detail results of roll center height changes.

Choosing Initial Roll Centers

Most racecar designers and racecar engineers tend toward low RCs, just above ground level. And they generally prefer a higher RC in the rear suspension than at the front. So a reasonable starting range for the front RC is from 2 in above the ground to an inch below and from 3 in to 6 in high in the rear. This configuration keeps jacking forces low, avoiding ride-height changes during cornering. The rear RC

is generally higher than the front because more mass is at the rear and the springs are softer. A higher RC decreases the roll moment, so less roll resistance is needed for the same roll angle.

Sometimes the rules of a racing series determines roll center location. In Chapter 11 we described the rear suspension required by NASCAR. This beam rear axle is located longitudinally by trailing arms and laterally with a Panhard rod, called a "track bar." Cars with a low front roll center height and a beam axle or high roll center in the rear generally have much softer springs at the rear than at the front because the rear is stiff due to the high roll center geometry. At the rear, the short CG-to-RC moment arm creates geometric stiffness. The direct force is large and the roll force small.

Varying track conditions might demand roll center changes. A wet track provides less grip so roll forces are low. Lowering the RCs so these roll forces are magnified might work better than drastic spring and bar changes. Likewise, a track with more grip might beg higher roll centers.

Roll Center Stability

Roll-center stability, how roll centers move with suspension movement, is important. In general you'd like the roll center to stay close to the longitudinal centerline of the car, but a few inches of lateral movement is fine.

And it's better if the RC moves up and down about the same as the CG of the car. That way roll forces don't change much as the suspension moves. If you have a light car that doesn't generate large lateral accelerations, this is less critical. But a downforce car with good tires can create high roll forces that can vary greatly as the RCs move.

Designers of racecars for the Trans-Am series made a rear-suspension change that helps stabilize vertical movement of the rear RC. They use a Watt linkage for lateral location of the rear axle housing, and this linkage determines the height of the rear RC. With the Watt-link pivot mounted on the rear axle housing, rear suspension vertical movement caused the RC to move vs. the CG, changing the magnitude of roll forces. After the design change the pivot is mounted on the chassis and moves with the CG, eliminating changes in the distance between the RC and the CG.

Roll Timing

When the driver turns the steering wheel entering a curve, the front tires move from zero slip angle to a slip angle dictated by driver input. Front lateral force builds from zero to some steady-state level. Lateral force at the rear also increases, slightly delayed from the front.

Inertial forces react to tire forces, accelerating the car toward the center of the turn and causing the chassis to roll on the suspension. The chassis is rigid to a large extent, so one end can't roll more than the other. The roll rate, however, must start slow and then increase when rear roll forces start to build.

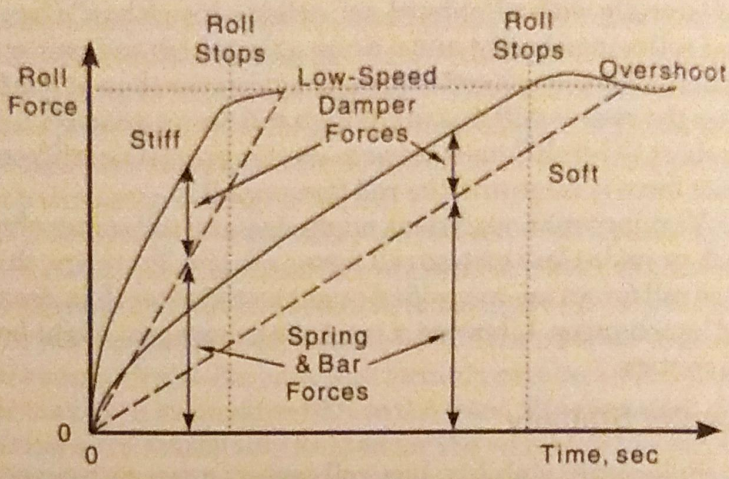

Fig. 13.8 Chassis Roll Dynamics, Stiff Setup and Soft

Fig. 13.8 describes roll timing for a soft setup and one that's more stiff. The vertical axis is the amount of roll-resisting force generated by the springs, bars, and dampers. The horizontal axis is time. It's obvious that a stiff setup builds roll resistance quicker than a soft setup. The dotted line across the top is the force trying to roll the car, which is proportional to the lateral force generated by the tires, the unsprung mass of the car, and the distance between the unsprung center of mass and the roll center. As soon as roll-resisting forces build up equal to the roll force, chassis roll stops. The chassis generates some roll inertia that might cause an overshoot depending on the level of low-speed damping. I showed some overshoot with the soft setup and a tapering-off of damper force with the stiff setup.

This graphic is only an approximation meant to show how damper/spring/bar forces build up to resist and eventually stop roll. I think the actual detail is much more complicated. For example, I think what actually drives chassis roll during the roll process is the instantaneous difference between the roll force and the resisting forces. If that's true then the rate of roll would slow as that difference decreased with roll. And, if roll rate slows, then damper forces decrease with roll. But that's way past the scope of this book, and I don't understand it well enough, anyway.

The timing of inertial forces is also different with roll center changes. A low RC causes a large roll moment and, unless restrained with big springs and bars, the car can feel sluggish and unresponsive. The car takes a long time to take a set when entering a turn. With higher roll centers most of the inertial forces go right to the chassis through the links as soon as the tires accelerate the car toward the center of the turn. The car feels responsive to the driver with less spring, bar, and damper stiffness.

Relative front/rear roll-center heights and front/rear roll stiffness determine how well the rear of the car follows the front. Everything happens first at the front of the car, because it's the steering input that starts the build up of tire forces and inertial forces. Roll-center heights are usually higher at the rear so that more geometric stiffness enhances the response of that end of the car.

Spring Preload

Racecars have adjustable spring perches that allow some static installed spring compression, called preload. With preload, the suspension doesn't move until the force on the tire contact patch (CP) exceeds the wheel rate dictated by the preload distance times the spring rate modified by the motion ratio. Spring preload is exactly the same as static friction in the suspension components, which is generally considered a bad thing. However, there are people who swear by preload, saying it results in lower lap times.

After a few discussions, I've come up with this explanation of preload effects. With some spring preload in the front suspension, a car entering a turn loads the outside contact patch more quickly. Since there is no roll yet, tire forces go directly to the chassis. When the preload is overcome, the normal roll rate takes over. Quick CP loading causes a rapid build up in lateral force, generating a similarly rapid build up of inertial forces. The car feels responsive and the tires might heat up more quickly, generating more lateral force earlier in the turn. It seems to me that a car would become more sensitive to preload adjustments as suspension static friction is eliminated.

If the car isn't severely grip-limited in mid-corner, this quick force/heat build up might increase total cornering force during the complete turn. Maybe that's why questions about preload come from people operating the lighter cars with wider tires—Formula Atlantic and Formula Ford 2000, for example.

Springs, Bars, and Dampers

Here's a simple summary of how these tuning components work. The springs support the car, keep it from hitting the ground, and resist body roll. Anti-roll bars resist body roll in addition to the springs, allowing softer spring rates, and they are a sensitive balance adjuster—cockpit adjustable if allowed by the rules. The dampers control the springs and prevent cyclic oscillations, helping the tires follow road irregularities. Dampers also control the rate of body roll, contributing to how the car feels to the driver. Now let's look at some details.

When the inertial forces roll the chassis, a specific amount of weight transfer is absolutely going to happen. The amount depends on the mass of the car, the lateral acceleration generated by the tires, the car's track width, and the height of the center of mass (CG). When the weight transfer occurs we want the car to have the maximum grip possible, so we want both ends of the car to reach the top of the force vs. slip-angle curve at the same time. We call that balance—no oversteer or understeer—but near-equal grip from both tire axle pairs.

We get balance by controlling the front-rear distribution of the total resistance to roll. The springs, dampers, and bars resist roll, and changes to these components change roll resistance distribution. But adjustments to these components work differently.

Springs and dampers generate forces in different ways. Springs and anti-roll bars generate force through displacement. A spring rated at 200 lb/in will give you 200 lb of force if you compress it one inch; it will generate 200 lb for every inch it is compressed; and the force is there as long as the spring is compressed. Anti-roll bars are similar. Displacement at one end twists the bar, producing a specific amount of force per unit of movement. The length of the moment arm of the bar makes a difference. A shorter arm produces more bar twist per unit of displacement and creates a stiffer bar than does a longer arm.

A shock absorber, which we'll call by its proper name, damper, doesn't care about displacement. You can move it through its full range with very little force if you move it slowly. But it is speed sensitive; it produces higher forces when displacement is faster. Dampers see higher-speed displacements when the suspension moves to absorb bumps at the tires, and damper forces add to spring forces, decreasing the amount of suspension movement during a bump. And, when the spring is compressed by a bump, high-speed damping prevents rapid rebound due to the stored energy in the compressed spring. In general a properly-adjusted damper helps minimize changes in tire contact-patch forces. Externally-adjustable dampers allow fine tuning of suspension characteristics for better grip.

The ride springs, anti-roll bars, and dampers resist body roll. Changes in spring rates and anti-roll bar stiffness affect balance in a very sensitive way. In the middle of a corner, roll-resistance distribution wedges or dewedges tire loading to determine balance. As we explained earlier, dampers add to roll-resistance but only when the chassis is rolling, during roll into a corner and de-roll out of a corner. Low-speed damper adjustment can wedge or dewedge tire loading during roll and deroll. The same adjustments also control how fast the car rolls (or how the front suspension rolls compared to the rear suspension), affecting the way the car feels to the driver. Again, external adjustments provide invaluable fine tuning of these sensitive handling characteristics.

Let's look at some detail and some choices.

The Anti-Roll Bar

These schematics will help us visualize what an ARB does to weight distribution. Fig. 13.9 shows a front ARB in the static position. The arrow shows how a shorter moment arm creates a stiffer bar. Fig. 13.10 illustrates how an ARB of this type twists during body roll. There are other ARB systems, but they all use body roll to deflect a spring and add roll resistance.

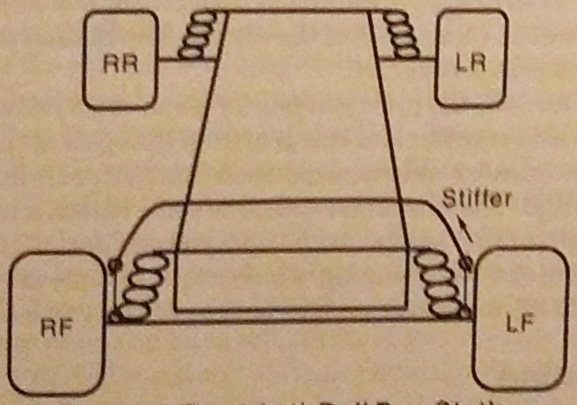

Fig. 13.9 Front Anti-Roll Bar, Static

In a turn, inertial forces roll the body and also transfer weight from the inside tires to the outside tires. An ARB adds to the total roll stiffness of the car, reducing the roll angle. But that roll stiffness comes at the expense of increased weight transfer at that end of the car, and that tire pair loses some grip. At the same time the other tire pair are more equally loaded and they gain grip. For a front ARB, the front tire pair loses grip and the rear pair gain, so this is an adjustment toward understeer and away from oversteer.

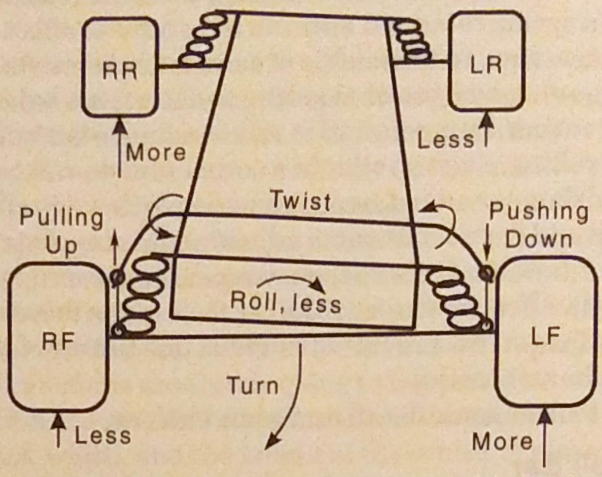

Fig. 13.10 Front Anti-Roll Bar Adds Roll Resistance, Understeer, and Wedge

Twenty years ago I read a quote in a magazine that really stuck with me, although I didn't understand it until much later. A racer said he'd never seen a front ARB that was too stiff. He drove a Camaro, a heavy, powerful, rear-wheel-drive car. That stiff ARB helped cure power oversteer at corner exit. He could somehow get it to turn into the corner even though it wanted to understeer, but he could really get into the throttle coming out of the corner. The hidden power of the ARB is wedge at corner exit.

With an ARB the price you pay for some extra roll stiffness is increased load transfer and less grip from that pair of tires. If the ARB is added to an independent suspension that system is less independent with the ARB. The wheels are linked to some extent when the ARB is in use. But an ARB lets you have more roll stiffness with softer ride-spring rates and less damping, which might provide more grip overall. It's a trade-off, and testing might be the only way to make a choice.

Skid-Pad Testing

Skid-pad testing can save track time and simplify the search for basic spring rates. Find a skid pad or lay one out yourself. Two hundred to 300 feet in diameter works well. Borrow some cones from a friend who autocrosses. Run the car equally clockwise and counter-clockwise. Record lap times, tire temperatures and tire pressures. This type of testing works with all cars. At speeds around 50 mph all cars have about the same grip potential.

Adjust balance by making changes to the spring rates and anti-roll bars. Remember that more roll resistance increases weight transfer across that axle and kills some grip at that end. Try to improve grip at the end of the car that's sliding. Work on the weak end of the car.

Springs and Bars: Choices

The first priority of the ride springs is to support the car. You need a spring stiff enough to keep the car from bottoming out anywhere on the track. Raising the ride height can also stop a car from bottoming.

Starting soft and adding spring rate is the best way to proceed. When the driver reports a flat slide at the limit with no balance problems, you've found your basic spring rates. Before you get to extremely stiff springs, add anti-roll bar stiffness to limit roll with softer main springs. Stiffening the ARB at one end means also stiffening the one at the other end to maintain balance.

Get the basic mid-corner balance with the springs and anti-roll bars. When you've picked the springs and bars, you've got the basic setup and changes can be made based on track variables. If one end of the car is sliding, try a change that makes that end softer. Remember that tires don't like incremental load. But soft spring rates can lead to excess suspension movement, causing camber problems and/or bottoming. You want the loaded tires to be vertical or have a slight amount of negative camber.

The end of the car doing the most work should be softer sprung. CART cars have a lot of horsepower and are traction limited up to speeds over 100 mph. They need roll stiffness at the front for more wedge at corner exit.

If the car is sliding around, go toward softer springs starting with the end of the car that is sliding more. When you get in a range where the car is balanced but rolling too much, stiffen the anti-roll bars one end at a time looking for less roll, better balance, and lower lap times.

A stiff car is very sensitive to speed, tire condition, and track condition. It will be fast if set up correctly, but you will have to chase the setup as the track and tires change. Remember that roll center heights also contribute to roll stiffness. You need to be aware of the trade-offs. You could choose low roll centers, control roll with stiff ride springs only, and have soft ARBs, or you could go another way and have stiff ARBs and soft springs. Or you could raise the roll centers for more geometric stiffness. As the lap times come down and the driver says the car feels good, tweak the ARBs to work toward a car that's just slightly on the understeer side of neutral in both directions.

When you encounter a track that has a lot of grip, the car is generating higher lateral force, more inertial force, and transferring more weight. The roll angle has probably increased, so all the resistance components will need to be stiffer. Stiffer springs and bars are obvious choices, but stiffer springs require damping changes also—more rebound and less bump. Instead of stiffer springs you could raise the roll centers to decrease the roll moment. A roll-center change could eliminate the need for stiffer springs and bars.

A low-grip situation dictates changes opposite to those in the last paragraph. Lower levels of lateral force decrease weight transfer as well as roll forces. Softer springs and bars, softer damping, or lower roll centers is the direction to go.

Damper Detail

As mentioned earlier, dampers are velocity sensitive. If you put a tiny bit of force on a damper, it will move slowly but steadily until it reaches the limits of its travel. But moving the damper quickly can take a lot of force depending on the internal valving of the damper.

Here's why that force variation with velocity is important. If a 100 lb/in spring is hooked up with the right damper, that damper will help the spring absorb the energy of a big compression input (bump), and when the spring is fully compressed and exerting maximum force, the damper resists a fast recovery of the spring. As the spring tries to recover quickly the damper exerts an opposing force that grows with velocity.

The 300 pounds of spring force caused by 3 inches of deflection becomes, as the spring recovers, 200 pounds at 2 inches deflection, 100 pounds at 1 inch deflection, and zero when the spring has fully recovered. The damper moves at some speed due to the 300 pounds of spring force and produces an opposing force to the spring. As the spring recovers toward zero displacement, spring force falls off, the damper slows, and damper forces fall off also. A damper is a speed-sensitive device.

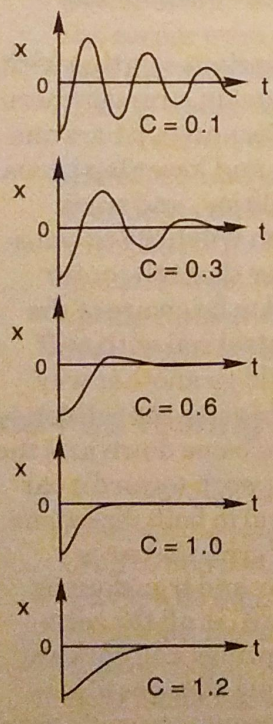

Fig. 13.11 Effect of Different Amounts of Damping

Fig. 13.11 shows the effects of different amounts of damping. These curves describe the motion of a spring/damper system that is displaced some amount and then released. If the damping coefficient, C, is 0.1 as in the top graph, the spring oscillates through several cycles before coming to rest. A car damped at that level might bounce around enough to make you ill.

As damping is increased the oscillations decrease until at C = 1, called Ccritical, the system returns to its equilibrium state with no overshoot. In the case of C = Ccritical, damper forces oppose spring recovery force so that both arrive at zero deflection at the same time. Road-car suspension systems are designed so the spring overshoots a little past perfect recovery and oscillates some before it settles back to zero deflection. An overdamped system—the damper stops spring

movement before the spring recovers to zero displacement—is certainly too harsh for a road-car suspension system but is used in racing applications.

A racecar on a track during a fast lap is changing speed and direction constantly. The track surface is uneven, and the car might go up and down hills and through banked corners or off-camber turns. We've been talking about the effect of tire contact-patch forces and how an adjustment in the static forces at the contact patch can affect how well the car handles. As the car goes around the track the spring and damper are both feeding forces into the suspension system. The spring forces vary with the amount the suspension moves. Damper forces vary with the speed of the suspension movement. Each tire patch sees a combination of forces from the spring and damper.

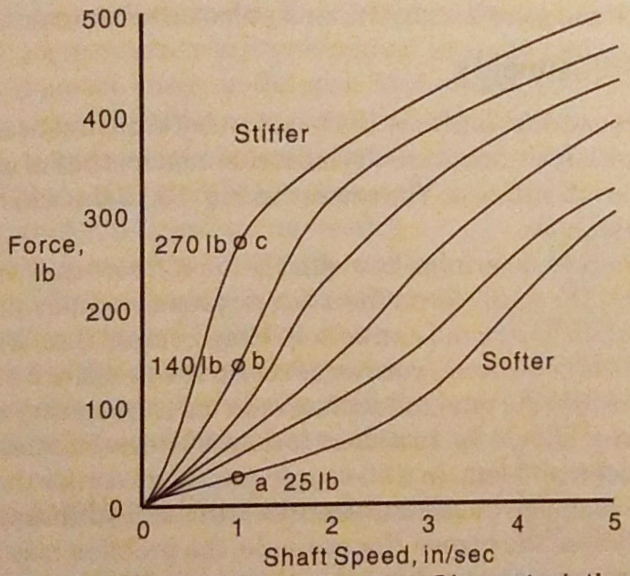

Fig. 13.12 Low-Speed Damper Characteristics

Fig. 13.12 shows a graph with a family of curves drawn from data taken on a damper dynamometer testing an Öhlins TT-44 damper. These curves are generated by adjusting the low-speed compression (bump) and the low-speed rebound. Each curve represents one specific setting for an adjustment knob on the damper. The forces for the rebound adjustments would actually produce negative force, but we only show one batch of curves. The adjustment mechanism is the same for bump and rebound, so the magnitude of the forces and the shape of the curves are the same with both adjustments. The TT-44 has

several other external adjusting mechanisms as well as several internal adjustments. All these variables modify the shape of the force vs. shaft speed curves of the damper.

This graph is important because is shows a large range of force adjustments at a relatively low shaft-speed. A car in a corner rolls due to inertial forces, causing relatively slow suspension movements. A damper that is adjustable in the shaft-speed range from zero to 2 in/sec can have a large effect on how quickly the chassis rolls. Small circles on three of the curves show forces generated at 1 in/sec for three adjustment examples, ranging from 25 to 270 lb. This adjustment affects tire performance and controls how the car feels to the driver.

The combination of forces from the spring, a displacement sensitive device, and the damper, which is velocity sensitive, results in an infinitely tunable system. This is extremely useful to the racecar engineer, allowing adjustments that help get the car to respond in a way that feels right to the driver. If the driver is comfortable in the car, he or she can go much quicker and still control the car.

Damper Adjustments

After springs and bars the next level of adjustment is the dampers. Dampers adjustments are the most common method of adjusting dynamic roll stiffness. You can see in Fig. 13.12 the wide range of forces available.

Dampers determine how quickly the roll occurs. Dampers also can affect the total roll stiffness (static plus dynamic roll stiffness) distribution during roll and de-roll. Keep in mind that, if the static roll stiffness is not correct, you can cover up the problem by adjusting dampers to bring total roll stiffness during corner entry and exit back to where it should be. In a short corner, 90 degrees or less, you may not notice a problem. In a 90-degree-and-more corner the car will have time to complete its roll and show its static roll stiffness handling in the middle of the corner. For example, the problem may show itself as "turns in great and washes out in the middle."

You need a 120- to 180-degree turn to set the roll and de-roll balance with the dampers. Again, if the previous two levels aren't correct you can to some extent correct this with dampers, but the setup window gets even smaller.

The following is a summary of damper adjustments. Remember, more equal contact-patch forces across an axle increase grip at that end of the car and improve grip at the other end.

When trying to improve overall grip during corner entry, work with bump adjustments at the front and rebound on the rear. Deceleration into a corner produces longitudinal weight transfer back to front, and the rear damper is extending as the front compresses.

When trying to get more overall grip at corner exit, first try rebound changes on the front and bump changes on rear. Acceleration out of a corner produces longitudinal weight transfer front to back. The front damper is extending as the rear compresses.

To correct corner-entry oversteer, increase bump on the front and/or decrease rebound in the rear. More bump at the front transfers more weight inside to outside, trending toward understeer. Less rebound at the rear transfers less weight, creating more grip at that end.

To correct corner-entry understeer, decrease bump on the front and/or increase rebound in the rear. Less bump at the front decreases weight transfer, increasing grip at that end. More rebound at the rear pulls weight off the inside rear, decreasing grip at that end.

To correct corner-exit oversteer, decrease rebound on the front and/or decrease bump on the rear. Less rebound at the front transfers more weight across the axle, reducing grip at that end. Less bump at the rear transfers less weight across the axle, producing more grip.

To correct corner-exit understeer, increase rebound on the front and/or increase bump on the rear. More rebound at the front decreases weight transfer at that end, increasing grip. More bump at the rear produces more weight transfer for less grip at that end.

With an almost infinite number of adjustment combinations, we've obviously barely scratched the surface of this subject. The goal here is to explain tuning concepts in terms of the tires. If you understand the reasoning behind the adjustments described above, you can apply that knowledge to other situations.

Tire Loads for Specific Adjustments

Fig. 13.13 describes the setup information and static tire loads for a basic car. This is a 2,000-lb car with equal weight distribution. We chose front springs that give us a 500 lb/in wheel rate, numerically equal to the 500-lb corner weight. The roll centers are near the ground and the rear is slightly higher than the front.

The information in Fig. 13.13 is required to make some basic calculations for weight transfer in a corner. We're going to say the car is in a flat corner at a

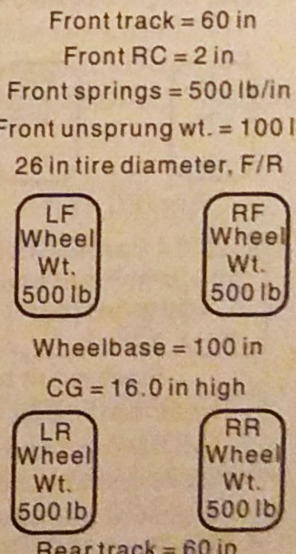

Fig. 13.13 Basic Car, Static

lateral acceleration of 1.2 G. Using our rules of thumb and some hypothetical driver feedback, we'll make some changes and look at the relative front/rear roll stiffness as well as the contact-patch loads to help make some decisions. What we're looking for is a combination of wheel rates, anti-roll bar rates, and roll-center heights that will give us a fairly balanced car with about one degree of roll.

For these calculations I used a software tool called *Racecar Engineering* developed by John Porcella. This program uses a more complicated calculation method than I used in the chapter on vehicle dynamics, so it's more accurate. I found the software easy to use and John's explanations make sense. The software is for sale and I've included John's contact information on a Resources page at the back of the book.

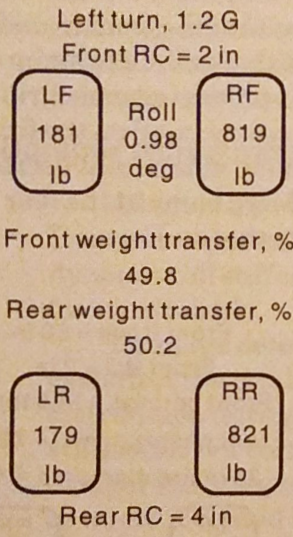

Fig. 13.14 Spring Choice, 500 lb/in Front and 400 lb/in Rear

Fig. 13.14 shows what happens if this car corners to the left with a lateral acceleration of 1.2 G. We have close to even front/rear roll stiffness, and we can see the actual contact-patch loading.

Since we're trying to choose wheel rates that will let us add anti-roll bars (ARBs) front and rear ,we need to soften these initial wheel rates so we'll have one degree of roll when we add the ARBs. For Fig. 13.15 we'll try 400 lb/in rate at the front and 300 at the rear. Notice this change resulted in more load on the inside rear tire.

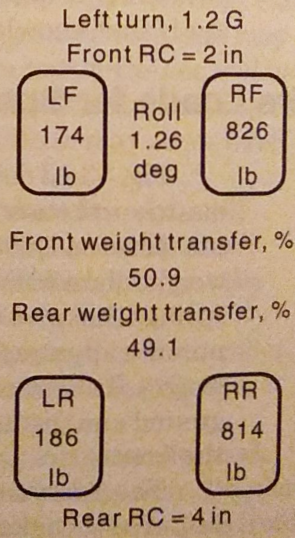

Fig. 13.15 Softer Springs, 400 lb/in Front and 300 lb/in Rear

We need to go softer still to lower the roll stiffness even more. Fig. 13.16 shows the result of a 300 lb/in rate at the front and 200 at the rear. This is the right direction and the percent-front weight transfer is going up. We just need to go still softer.

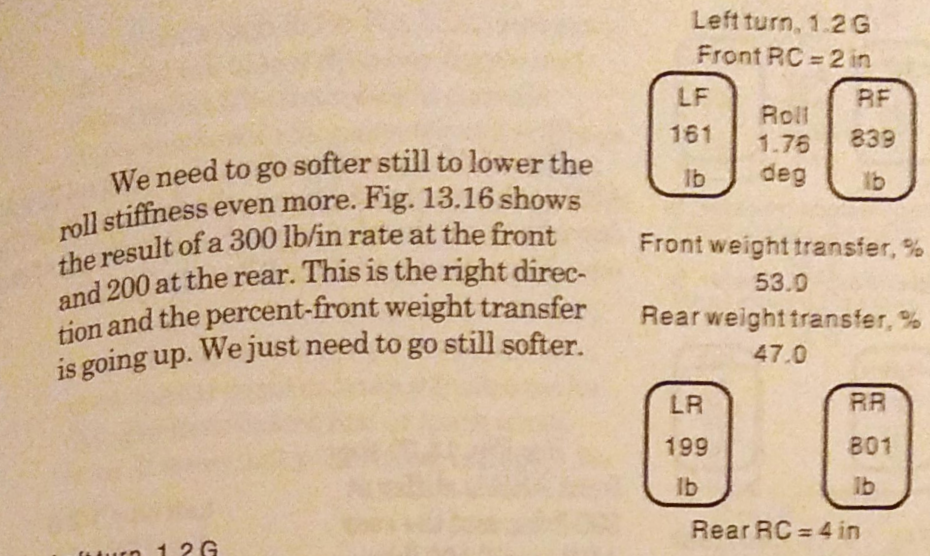

Fig. 13.16 Still Softer, 300 lb/in Front and 200 lb/in Rear

For Fig. 13.17 we're down to 200-lb/in wheel rates at the front and 150 lb/in at the rear. Roll is up to 2.52 degrees. We'd like more total roll stiffness to lower the roll angle and more roll stiffness at the front for some additional wedge at corner exit.

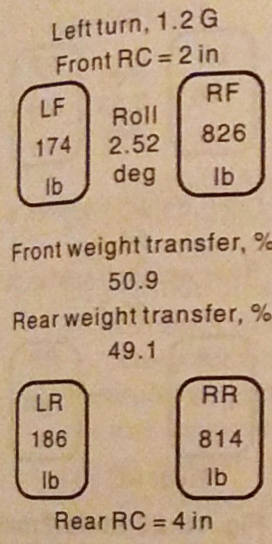

Fig. 13.17 Softer Still, 200 lb/in Front and 150 lb/in Rear

We've added a front ARB in Fig. 13.18, one that has a spring rate of 100 lb/in. The roll stiffness is now more than 60% at the front, and the total roll is down to 1.60 degrees. Let's add a rear ARB.

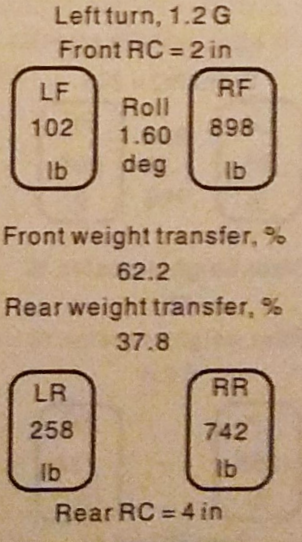

Fig. 13.18 Add Front Anti-Roll Bar, 100 lb/in

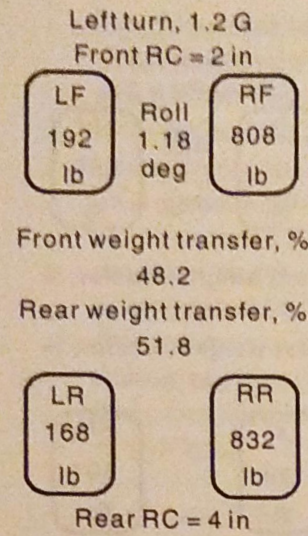

Fig. 13.19 Add Rear Anti-Roll Bar, 100 lb/in

Fig. 13.19 shows the effect of adding a 100 lb/in ARB at the rear in addition to the front ARB. Roll is down but now there's too much roll stiffness at the rear. How about a stiffer ARB at the front?

For Fig. 13.20 the front ARB is stiffer at 200 lb/in, and the rear ARB is still 100 lb/in. Roll is now a little less than one degree and we've got about 55% of the weight transfer happening at the front tires. Our driver says there is less power oversteer.

But our driver also tells us the rear of the car is moving more than the front. It's not oversteer because the front tires are sliding mid-corner and the car can handle more throttle at corner exit without a lot of oversteer.

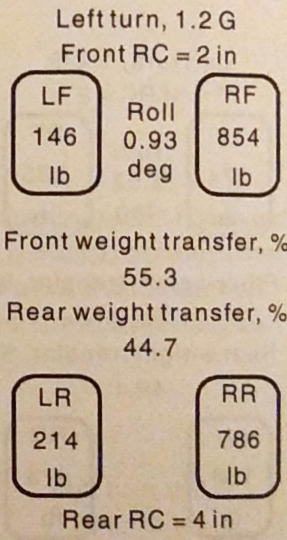

Fig. 13.20 StifferFront Anti-Roll Bar, 200 lb/in

If we raise the rear roll center, we add some geometric stiffness. Let's unhook the rear ARB and raise the RC from 4 in to 6 in.

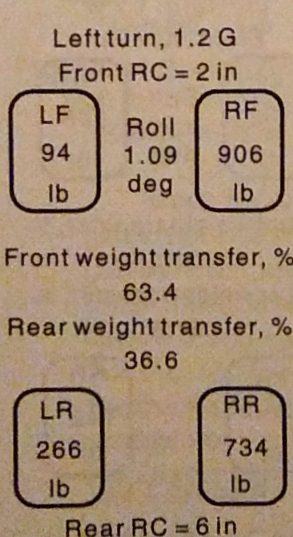

Fig. 13.21 Higher Rear RC, No Rear ARB

In Fig. 13.21 the front weight transfer has gone way up because we got rid of the rear ARB. Our driver tells us the car is pushing like a pig, so we need to raise the rear RC more than 6 in.

A 10-in high RC in Fig. 13.22 decreases the total roll to less than one degree and restores our 55% front weight transfer. We've increased the geometric roll stiffness by raising the rear RC. Notice the contact-patch loads are almost identical in Fig. 13.21 as they were in Fig. 13.20 when an ARB at the rear provided some rear roll stiffness.

So we don't need a rear ARB. We still have a front ARB, which, if it's adjustable, gives the car some balance adjustment for changes in on-board fuel or track conditions. If we're lucky the driver is happy, for now.

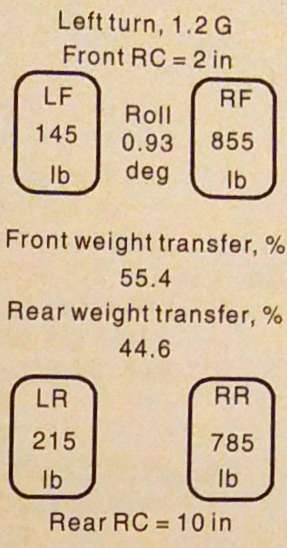

Fig. 13.22 Still Higher Rear RC

That's it! Although we could go on indefinitely looking at setup adjustments and the resulting detail changes in tire contact-patch loading, these examples should explain the concepts. Hopefully the information presented here will help some people better understand an extremely complicated subject.

The goal of motor racing is a quicker lap time on a certain day at a particular racetrack. With the innate variables in tires, drivers, dampers, and ambient conditions, this goal is difficult to achieve. Which, of course, is what makes motor racing such a challenge. Be thankful it's not less complicated. Then anyone could do it!

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